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July 2022

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Carbon Capture Landscape 2022

Still Early to Confidently Fulfil Carbon Capture and Removal Promises

Executive Summary

The Intergovernmental Panel on Climate Change (IPCC) released its Sixth Assessment report[1] in April 2022. The nuance of what was heard likely depends on where interests lie. Some argue the recent report gives the green light for continued fossil fuel use with carbon capture and storage[2] (CCS), while others contend it was a signal to close the door on CCS and keep the focus on proven technologies. The truth on such divisive topic is complex.

CCS is often discussed in the context of gas processing or thermal power generation. However, CCS covers various technologies and processes. It is important for investors to be clear about the type of CCS being discussed, as the different applications have varying levels of technical and commercial maturity, contrasting environmental and social risks and opportunities, and differing mitigation potential.

This report outlines the general status, risks and opportunities of carbon capture technology in various applications. The key findings are summarised as follows:

The availability and quality of data from the testing and operations of CCS across all applications is generally weak, which makes the real technology, commercial readiness level, and cost competitiveness uncertain.

Gas processing is the main CCS application globally.[3] However, due to its association with enhanced oil recovery (EOR) and historic capture rate issues[4,5], it has minimal environmental and social credibility as a decarbonisation option.

Power and blue hydrogen are the new use cases of CCS to decarbonise the power and industrial sectors, respectively. But these applications are not commercially advanced and raise several environmental concerns. As IEEFA

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[1] IPCC Sixth Assessment Report Climate Change 2022: Mitigation of Climate Change, April 2022.

[2] The term CCS is used throughout the report. CCS/CCUS are often used interchangeably, the key difference being the inclusion of U(tilisation) of CO2. CCUS may also be applicable to all applications in this report.

[3] Global CCS Institute, Global Status of CCS 2021, 2021, p.63-66.

[4] IEEFA, Carbon Capture to Serve Enhanced Oil Recovery: Overpromise and Underperformance, Robertson and Mousavian, Mar 2022, p18-20.

[5] IEEFA, Gorgon Carbon Capture and Storage: The Sting in the Tail, Robertson and Mousavian, Apr 2022, p.1-3.

previously reported[6] [7], CCS for power generation has also been challenged in meeting the industry target capture rates. It is generally not seen to be cost competitive with renewables and storage as a climate change mitigation option for the power sector.

In industrial applications, CCS with permanent storage appears to provide a viable mitigation option for ethanol and fertiliser production. In other industrial applications, such as steel and cement, CCS is being explored for technical and commercial competitiveness at a commercial scale. However, with current high commodity prices, green hydrogen is becoming increasingly cost competitive[8] and will attract potential green hydrogen pathways such as green steel and green fertiliser. Cement calcination with CCS may be the most viable pathway for deep decarbonisation of the cement industry. CCS projects in industrial applications have also been associated with EOR projects, although there is a positive trend globally of projects towards dedicated geological storage.[9]

Carbon Dioxide Removal Technologies (CDR)—Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS)—are not well advanced technically and commercially. However, should they prove cost-competitive and commercially robust technologies, they offer environmental and social usefulness by providing the possibility of negative emissions to prevent global emissions overshoot.

As there are still many unknowns and risks with carbon capture technologies, global focus should remain on the least cost, low-hanging fruit to support the energy transition. In most contexts, this is in the form of renewable energy deployment, electrification and supporting grid modernisation investments to help move renewable energy to where and when it is needed. Additionally, targeting low-cost vehicle electrification opportunities to reduce tailpipe emissions, and investing in monitoring and abating methane leakages from gas extraction provides cost-competitive abatement solutions.

If emissions cannot be abated at lower cost and effort by other means in hard-to-abate industrial and heavy and marine transport, then CCS and carbon dioxide removal (CDR) technology (BECCS and DACCS) become compelling and may be needed to reduce emissions.

As CCS has only been meaningfully commercially deployed in gas processing, ethanol and fertiliser production, and performance and costs have not been verified by third parties, the actual costs of CCS are largely untested and, in most cases, unproven. When the technology is consistently demonstrated at commercial-scale,

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[6] IEEFA, Where's the Beef?: Enchant's San Juan Generating Station CCS Retrofit Remains Behind Schedule, Financially Unviable, David Schlissel, May 2021, p.1.

[7] IEEFA, Blue Hydrogen: Technology Challenges, Weak Commercial Prospects, and Not Green, Schlissel, Wamsted, Feaster, Mattei, Mawji & Sanzillo, Feb 2022, p.18 .

[8] Recharge News, Green hydrogen now cheaper than blue in Middle East, but still way more expensive in Europe, 24 Feb 2022.

[9] Global CCS Institute, Global Status of CCS 2021, 2021, p.63-66.

project costs and technical performance will need to be made available and verified to understand the actual deployment and mitigation costs.

The most socially and environmentally impactful applications of CCS in industrials, BECCS and DACCS, are immature, both technically and commercially. If these are to have an impact, progress needs to be made to rapidly advance and scale the technology. Additionally, the permanence of carbon dioxide (CO2) storage will need to be proven over a millennia timescale. This will require appropriate monitoring and verification standards, liability frameworks, and additional emissions buffers to protect the climate and public from CO2 leakage.[10]

Given the status of technology and the balance of risks, there is significant evolution that carbon capture technologies need for them to be technically proven and commercially viable at scale, and therefore bankable. A key impediment to investment is the lack of availability and weak quality of data from the testing and operations of CCS across all applications, which makes the real technology, commercial readiness level, costs and cost competitiveness uncertain.

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[10] ETC, Mind The Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive, March 2022, p.63-64.

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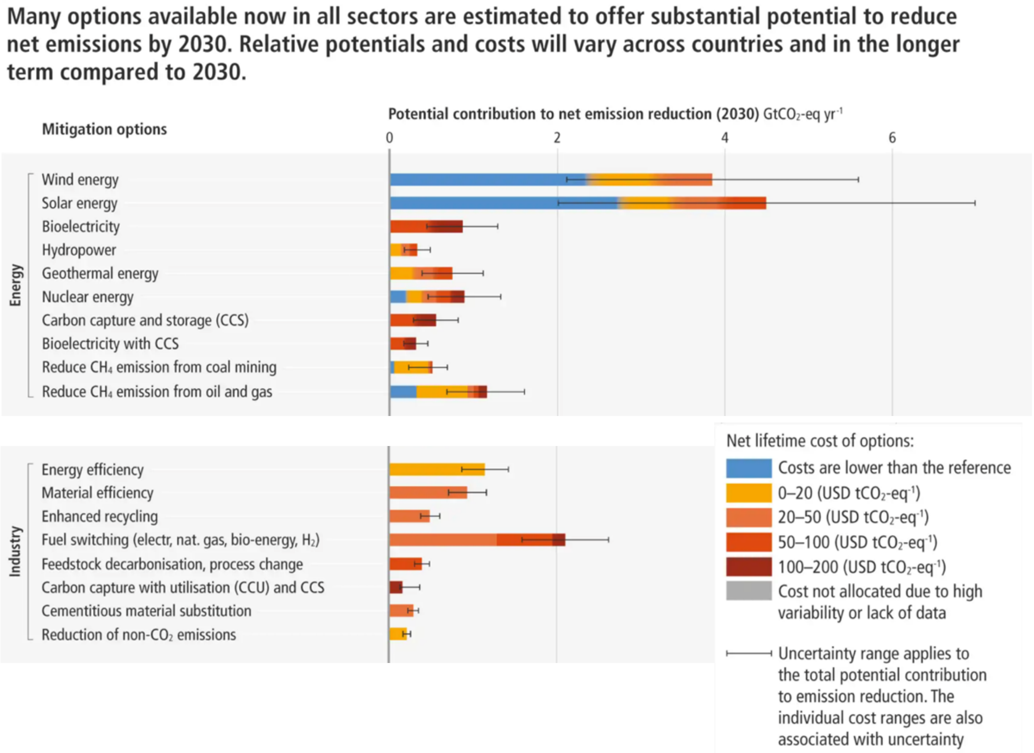
Latest from IPCC

In April, the Intergovernmental Panel on Climate Change (IPCC) released its Climate Change 2022: Mitigation of Climate Change report related to the Sixth Assessment Report. The report created a lot of discourse in the public domain for its stance on Carbon Capture and Storage (CCS) and Carbon Dioxide Removal (CDR) technology. Scientist Rebellion[11] have argued that several governments had hijacked the IPCC text with a vested interest in keeping fossil fuels alive. Others[12] [13] support IPCC's argument that this is the stark reality, and that carbon capture technology (covering both CCS and CDR technology) is critical to our collective net-zero efforts.

Figure 1: A role for CCS in our net-zero future?



Source: IPCC 2022 Report[14]

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[11] Scientist Rebellion, We have leaked the upcoming IPCC WGIII report, 2022.

[12] IEA, CCUS in Clean Energy Transitions, Sep 2020, p.13

[13] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, M., P. Durrant & K. Kochhar, Oct 2021, p.8

[14] IPCC Sixth Assessment Report Climate Change 2022: Mitigation of Climate Change, April 2022, p.50.

Key messages from the IPCC Report

The IPCC Report notes that reducing CO2 emissions via electrification or the use of alternative fuels will likely prove cheaper and more rapidly adopted options than CCS in most contexts. Additionally, eliminating large volumes of fugitive methane emissions from fossil-fuel extraction can be done at lower costs than CCS. And, as IEEFA and others have argued, the focus and hopes of CCS may distract attention away from lower-cost renewables and lead to a prolonged transition away from fossil fuel use.[15] [16] [17] [18] It may also divert physical and financial resources from renewable energy and energy efficiency applications.

Yet, some stakeholders say that there is a chance that eliminating emissions in the next decade or by 2050 may need to rely on CCS as an option. DNV (one of the largest technical consultancy and supervisory service providers to the global renewable energy and oil and gas industry) considers that the transition to fossil-free by 2050 is not feasible.[19] They estimate that 16% of fossil fuels will remain in the global energy system in 2050, and 20% of emissions cuts will have to be in the form of carbon capture and removal.[20]

In harder-to-abate industrial sectors, such as steel and concrete, CCS is seen by some as a viable option for cost-effective, scalable emissions reductions.[21] But with no commercial-scale cement projects (several planned[22]) and only one commercial-scale facility for steel (and no plans for any major steel projects with CCS[23]), the validity of that claim is yet to be tested. Hydrogen-based production of industrials, such as steel, is emerging as the preferred and potentially the most efficient option.[24] However, green hydrogen (i.e. hydrogen produced from renewables) is becoming more competitive[25] and with recent global energy commodity price increases has already become cheaper in some regions.[26] Other analyses suggest

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[15] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, M., P. Durrant & K. Kochhar, October 2021, p.8

[16] AIGCC, Carbon Capture and Storage in the decisive decade for decarbonisation: The case for Asia, Mar 2022, p.3.

[17] IIGCC, Global Sector Strategies: Investor Interventions to Accelerate Net Zero Electric Utilities, Oct 2021, p.36

[18] Letter from scientists, academics, and energy system modellers: Prevent proposed CCUS investment tax credit from becoming a fossil fuel subsidy, Hoicka et al., Jan 2022.

[19] DNV, Pathway to Net Zero Emissions: 1.5 degrees is possible if everybody lifts what they can, 2021.

[20] ibid.

[21] IEA, CCUS in Clean Energy Transitions, September 2020, p.17 & 65.

[22] Global CCS Institute, Global Status of CCS 2021, 2021, p.63-66.

[23] Agora Industry,Wuppertal Institute and Lund University. Global Steel at a Crossroads: Why the global steel sector needs to invest in climate-neutral technologies in the 2020s, 2021, p.11.

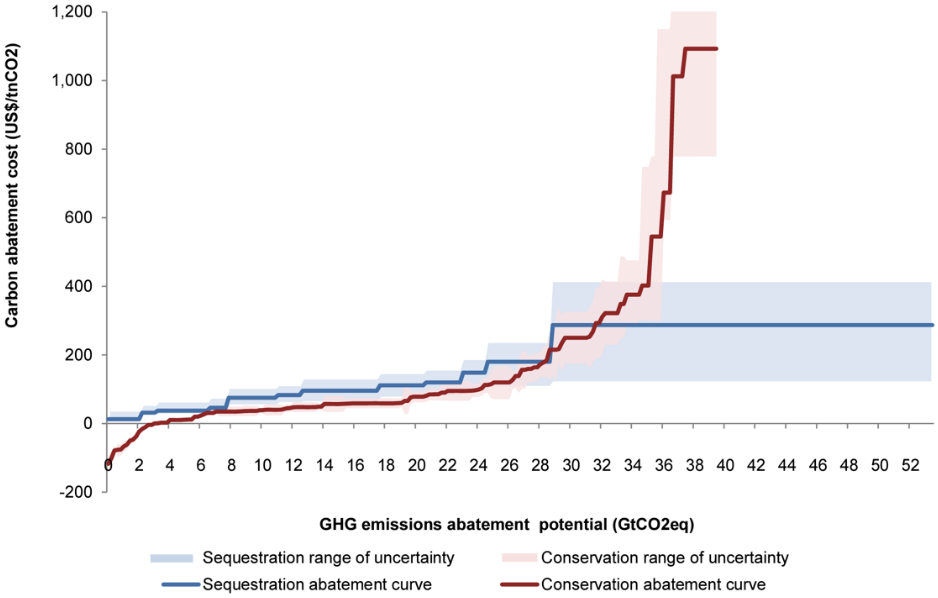
[24] S&P Global, Dutch CCS project scrapped after Tata Steel opts for hydrogen DRI production route, 21 Sep 2021.

[25] S&P Global, Experts explain why green hydrogen costs have fallen and will keep falling, 5 Mar 2021.

[26] Recharge News, Green hydrogen now cheaper than blue in Middle East, but still way more expensive in Europe, 24 Feb 2022.

that globally hydrogen will only start to be globally competitive and a preferred option in the 2030s.[27,28,29]

Figure 2: Sequestration versus abatement costs



Source: Goldman Sachs 2019[30]

Bloomberg New Energy Finance's (BNEF) *Gray Scenario* to net-zero by 2050 is their estimated least-cost pathway to net-zero. It relies in part on CCS and requires $3.1 trillion of investment in energy over each of the next three decades.[31] BNEF notes that CCS for fossil-fuels is included in the *Gray Scenario* and reduces higher cost buildout of total infrastructure to produce 1,318 million tonnes of hydrogen required for their *Green Scenario.*[32] IEEFA notes that recent global energy shocks have improved the relative economics of green hydrogen, and likely will bring a faster push into green hydrogen (at whatever cost), as with the RePowerEU four-fold increase in 2020 green hydrogen targets.[33]

The IPCC 2022 Report also notes that net-zero energy systems and pathways likely to limit warming will require some amount of CDR to accelerate the pace of emissions reductions and to compensate for residual greenhouse gas (GHG)

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[27] Wood Mackenzie, Can green hydrogen compete on cost?, 7 Dec 2021.

[28] DNV, Pathway to Net Zero Emissions: 1.5 degrees is possible if everybody lifts what they can, 2021.

[29] IEA, Global Hydrogen Review 2021, p.19.

[30] Goldman Sachs Research, Carbonomics: The Future of Energy in the Age of Climate Change, 11 Dec 2019, p.14.

[31] BloombergNEF, The Role of Carbon Capture and Storage in Getting to Net-Zero by Mid-century: New Energy Outlook 2021, 30 Sept 2021.

32 ibid.

[33] Goldman Sachs Research, Carbonomics: Security of Supply and the Return of Energy Capex, 17 Mar 2022, p.1.

emissions. CDR technologies offer optionality to solve for delayed action and help provide a solution for hard to abate sectors even at the current high-cost estimates.[34] [35] However, others argue that considering these technologies will justify inaction on climate change.[36]

The storage of CO2 is an important part of the CCS pathway if it is to be considered a viable climate solution. If CO2 use or storage (such as EOR) results in a net increase in emissions, then CCS should not be considered a decarbonisation option. The IPCC notes that, in theory, there is enough capacity globally to store required CO2 to limit the temperature to 1.5°C, although the regional availability of geological storage could be a limiting factor.[37] However, even if CO2 is expected to be permanently stored, the permanence of storage over a long-time scale will need to be monitored. Appropriate monitoring and verification standards, liability frameworks, and additional emissions buffers are in place to protect the climate and public from leakage.[38]

Depending on the methods used and the context they operate in, CDR technologies may provide co-benefits for ecosystems and soil sequestration or may have negative impacts on environment and sustainable development goals.[39] The required scale and timing of the deployment of CDR technologies will depend on the mitigation actions taken in this decade and the trajectory this sets us upon. CDR projects are most likely to be deployed in jurisdictions with appropriate carbon pricing or tax incentives.

Significant improvements in technology, cost and more commercial applications are needed in the coming decade in order to deliver on the promises that carbon capture technology advocates have now made.[40]

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[34] Carbon Brief, Direct CO2 capture machines could use 'a quarter of global energy' in 2100, 22 Jul 2019.

[35] Energy Transition Commission (ETC), Mind The Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive, March 2022, p. 9.

[36] Political Geography, Volume 88, Limits to climate action: Narratives of bioenergy with carbon capture and storage, Haikola, Anshelm & Hansson 2021, p.4-5.

[37] IPCC Sixth Assessment Report Climate Change 2022: Mitigation of Climate Change, April 2022, p.37.

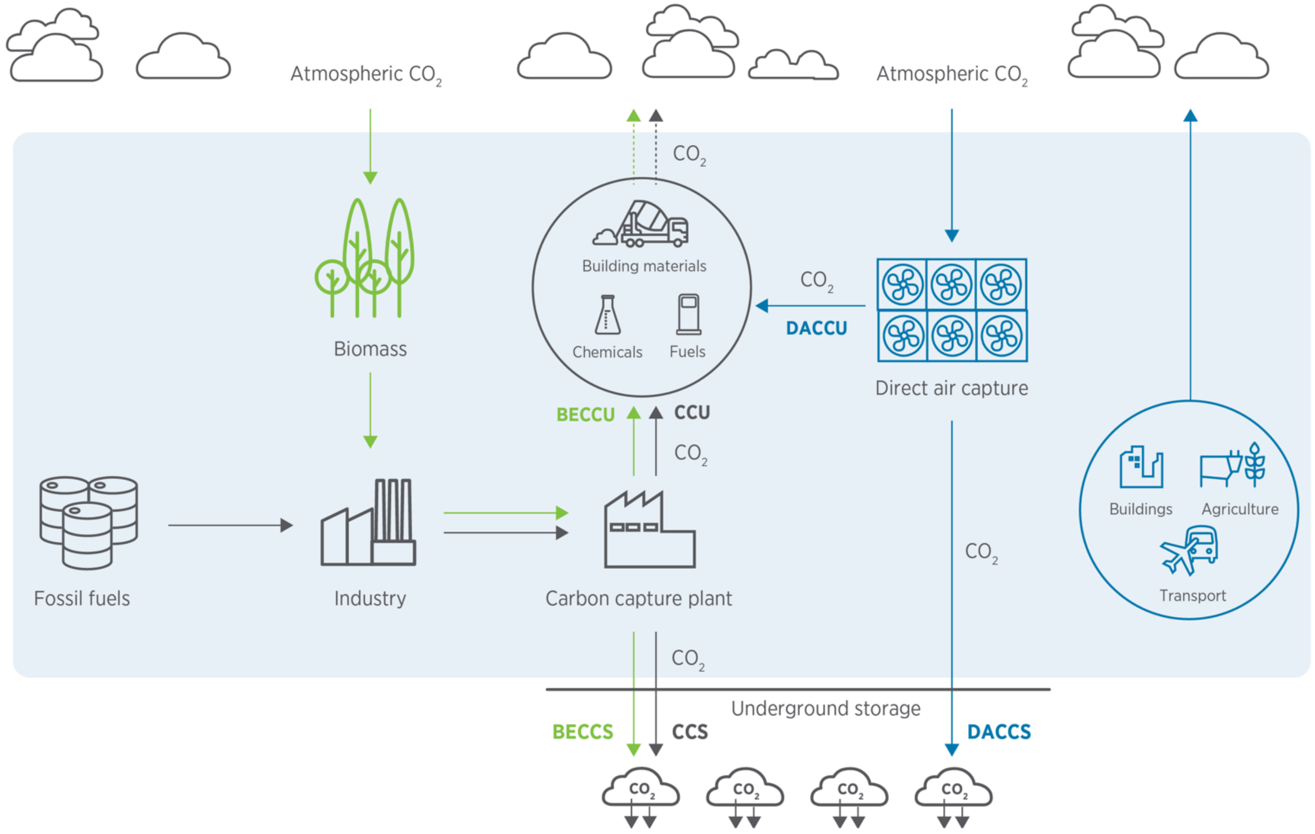
[38] ETC, Mind The Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive, March 2022, p.63-64.

[39] Carbon Brief, In-depth Q&A: The IPCC's sixth assessment report on climate, 9 Aug 2021.

[40] BNEF, Getting on Track for Net-Zero by 2050 Will Require Rapid Scaling of Investment in the Energy Transition Over the Next Ten Years, 21 Jul 2021.

Carbon Capture Landscape

Figure 3: Carbon Cycle



Source: IRENA[41]

CCS directly captures CO2 from a point source (such as a power plant or industrial facility), then compresses, transports and stores CO2. Storage should be permanent to qualify CCS as a climate mitigation option.

CCS can be applied to various sectors and covers a wide range of technologies and processes, varying levels of technical and commercial maturity, different environmental and social risks, and differing mitigation potential. As IEEFA has previously noted, the topic of CCS can be confusing for the uninitiated reader and needs to be untangled.[42]

This review does not provide a deep dive into the technologies or processes, but rather provides a summary of the different applications of CCS. The report breaks down CCS into six categories of distinction that are important to consider.

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[41] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, M., P. Durrant & K. Kochhar, Oct 2021, p.14.

[42] IEEFA, Carbon Capture in the Southeast Asian Market Context, Putra Adhiguna, Apr 2022, p.2.

A Note on Carbon Capture and Utilisation (CCU)

CCU and CCUS are derivations of CCS applications. The key difference being the inclusion of the utilisation of CO2. CCU is where captured CO2 is then used for industrial processes such as synthetic fuels, chemicals, and materials. CCUS is where CO2 is utilised and stored, such as enhanced oil recovery (EOR) or enhanced gas recovery (EGR). EOR is the most prominent use case where CO2 is used for EOR to push more oil out of oil fields.[43]

Utilisation of CO2 in EOR (or EGR), plastics and materials will generally lock the CO2 away, however EOR will also produce more oil out of oil wells. Utilisation in fertilisers or synthetic fuels will also result in release of the CO2 upon use. In use scenarios, where primary CO2 production is displaced, there may be a lifecycle benefit, however there is concern about the continued use of fossil fuels and impact of CCU on emissions is complex and divisive.

CCS for Gas Processing

Gas processing facilities often have to separate CO2 from the extracted gas in order to produce a sellable gas product. The CO2 captured is typically vented but can be stored.

CCS facilities have been operating since the 1970s at gas processing facilities. CO2 is captured and then generally injected into oil wells to increase oil quantities, a process known as enhanced oil recovery (EOR). CCS has subsequently evolved over the years to inject CO2 into large geological storage reservoirs (including saline formations or depleted oil reservoirs).

CCS for Power Generation

Power plants (or generators) using fossil fuels (coal and gas) produce a byproduct of electricity production known as flue gas. This flue gas contains a mix of nitrogen, CO2, water vapour, some other gases and particulate matter. CCS technologies are designed to be built into new facilities or retrofitted to old facilities, and capture the CO2 from flue gas, typically via chemical absorption (or other emerging methods). The CO2 is transported, used and/or stored.

CCS for Industrials

Heavy industries are responsible for around 30% of global CO_2 emissions.[44] The top three emitters are steel, cement and chemical production. CCS has been applied to ethanol and fertiliser production at commercial scale. CCS technologies and projects are also being developed that may (or may not) provide viable options to reduce emissions more than alternatives in steel, cement, and hydrogen production. [45] [46]

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[43] Global CCS Institute, Global Status of CCS 2021, 2021, p.63-66.

[44] Our World in Data, Emissions by Sector, 2021, Ritchie & Rosie.

[45] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, Durrant & Kochhar, Oct 2021, p.63 -76.

[46] AIGCC, Carbon Capture and Storage in the decisive decade for decarbonisation: The case for Asia, Mar 2022

In the cement industry, decarbonising process emissions would account for around 60% of cement industry emissions[47], equating to approximately 4 - 5% of global emissions. However, this technology is not yet operational at commercial-scale.[48]

CCS for Blue Hydrogen

Hydrogen is derived from natural gas via the process of steam methane reforming with CCS applied to separate the CO2 from the hydrogen. The resultant 'Blue Hydrogen' is said to be a 'low-carbon'[49] energy vector if the CO2 emissions are captured and permanently stored.

BECCS

In BECCS[50] technology, the process captures CO2 directly from the atmosphere via plant growth, and then combusts plant-based material in a power (or heat) generator fitted with CCS technology. Through this process, the CO2 is captured from the atmosphere, resulting in net negative emissions. If technical and sustainability issues can be resolved, BECCS could have a positive impact in biorefineries, power, heat, chemicals, cement, pulp and paper, and sugar production, and possibly also iron and steel production.[51]

DACCS

In DACCS technology, direct air capture technology is combined with CCS. Direct air capture is a process of capturing the CO2 directly from the atmosphere using technology. DACCS is a nascent technology and is expected to be the most difficult and highest cost of carbon capture applications because of the dilute nature of CO2 concentration in the atmosphere (as compared with a process stream).[52] DACCS projects face high costs, technical challenges, and high energy and land requirements, yet offer flexibility in their location.[53]

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[47] The Conversation, Relying on carbon capture to solve the climate crisis risks pushing our problems into the next generation's path, 4 May 2022.

[48] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, Durrant & Kochhar, Oct 2021, p.63 - 67.

[49] There is significant controversy around the "low-carbon" claim for blue hydrogen that is considered later in this report.

[50] BECCS and DACCS are referred to as Carbon Dioxide Removal (CDR) technologies. This refers to technology that captures CO2 directly from the atmosphere, and then may be either utilised or stored. When CO2 is stored for a long duration it results in negative emissions.

[51] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, Durrant & Kochhar, Oct 2021, p.11.

[52] Global CCS Institute, Global Status of CCS 2021, 2021, p.59.

[53] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, Durrant & Kochhar, Oct 2021, p.33.

Assessing the Status of Current CCS Applications

The landscape of CCS is varied, as previously discussed. The following provides a review of the different applications of the technology to help provide insight into the current status. The review considers market share, technology and commercial readiness, cost competitiveness, and environmental and social risks. The following criteria are reviewed for each of the CCS applications and discussed in the following sections.

Current Capture Share

The operational capture capacity of the CCS application is considered and compared to the other facilities using the Global CCS Institute data.[54]

Technology Readiness

The technology is qualitatively assessed against the Technology Readiness Level (TRL) benchmark. NASA originally developed the TRL and now TRL is a globally used framework to measure the maturity of technology projects, from research to demonstration.[55]

Commercial Readiness

The Commercial Readiness Index (CRI) framework[56] was developed by the Australian Renewable Energy Agency (ARENA) to assess the "commercial readiness" of renewable energy solutions. Although not a renewable energy technology, it provides a useful framework for rating energy projects.

Each application's environmental risks and potential benefits are qualitatively discussed.

Environmental Credibility

Each application's environmental risks and potential benefits are qualitatively discussed.

Social Risks

Each application's social risks and potential benefits are qualitatively discussed.

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[54] Global CCS Institute, Global Status of CCS 2021, 2021, p62-66. Noting that the Global CCS Institute has a vested interest in promoting the performance of CCS technology.

[55] Australian Renewable Agency (ARENA), TRL Guide, 2019.

[56] ARENA, Commercial Readiness Index for Renewable Energy Sectors, 2014.

Current Market Share

There are 27 commercial-scale fossil fuel-based CCS facilities (compared with thousands of renewable projects) in operation. These facilities only capture around 40 million tonnes per annum (Mtpa) of CO2 and generally have not yet performed as expected.[57]

CCS for Gas Processing

According to data from the Global CCS institute[58], of the 27 operational CCS facilities, gas processing accounts for 12 (~44%) of the facilities. These 12 facilities account for around 70% of CO2 capture capacity, and the majority of this capacity is being used for EOR operations.

CCS for Power

Since the Petra Nova coal-fired power generation plant in the United States suspended CO2 capture operations in May 2020, there is only one commercial power plant equipped with CCS in operation today. This project (Boundary Dam) currently represents 2.5% of global CO2 capture capacity. According to the International Energy Agency (IEA)[59], there are plans for over 40 CCS for power projects, including five in China. The potential capture capacity of all CCUS deployment in power is projected to reach ~60 Mtpa CO2 in 2030.[60]

CCS for Industrials

There are eleven industrial facilities with CCS that capture a total of 7 Mtpa of CO2 globally.[61] Nearly all (92%) of these facilities are chemical facilities, and almost all (90%) are tied to EOR operations. There is only one fully commercial steel CCS facility globally, which has been operating in Abu Dhabi since 2016[62] and is associated with EOR.[63] There are no commercial cement facilities with CCS but one pilot project and a growing list[64] of projects in various stages of development. BNEF notes to get on track for net-zero by 2050, CCS in cement and steel needs to move beyond pilot and demonstration projects and significant cost reductions.[65]

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[57] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, Durrant & Kochhar, Oct 2021, p.10.

[58] Global CCS Institute, Global Status of CCS 2021, 2021, p.63-66.

[59] IEA, CCUS in Power, 2021.

[60] ibid.

[61] Global CCS Institute, Global Status of CCS 2021, 2021, p63-66.

[62] Scottish Carbon Capture & Storage (SCCS), Global CCS MaP: Al Reyadah: Project Details,

[63] Carbon Sequestration Leadership Forum, Al Reyadah Carbon Capture, Use, and Storage (CCUS) Project.

[64] Global Cement, Towards net-zero: Low CO2 cement production, 4 Mar 2021.

[65] BloombergNEF, Getting On Track for Net Zero This Decade, Matthias Kimmel, 1 Feb 2022.

CCS for Blue Hydrogen

Approximately 120 Mtpa of hydrogen is produced annually, but only around 2 Mtpa (~0.6%) of this is produced from blue hydrogen.[66] There are three facilities (located in the US and Canada) that produce blue hydrogen accounting for almost 4 Mtpa of carbon capture capacity.[67] As reported by IEEFA[68], the current scale of blue hydrogen is unimpressive, with only two commercial plants capturing more than 1 Mtpa. The Global CCS Institute lists five projects in advanced development with another eight in early development[69], however this is a long way from the required levels.

BECCS

According to the International Renewable Energy Agency (IRENA), there are three commercial BECCS facilities capturing a total of just over 1 Mtpa of CO2.[70] These facilities are all ethanol production with CCS and only one is storing CO2 while the other two are utilising CO2 for EOR. Six more projects due within the next decade[71], adding 6.73 Mtpa of capture capacity to the total. Major projects such as the Drax power station with BECCS and the Exergi KVV8 facility are expected to demonstrate significant progress for BECCS in Power.[72] However, the project pipeline is a long way from the contributions imagined by the IPCC.

DACCS

There are only three commercially operating plants, and these capture an insignificant volume of (around 10 ktpa) CO2[73] [74]. This is several orders of magnitude away from the potential 5,000 - 40,000 Mtpa listed in the IPCC Report. There has been some progress in developing larger commercial facilities, with 1PointFive entering into the Front End Engineering and Design (FEED) phase for its 1 Mtpa DAC facility in the U.S. Permian Basin.[75]

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[66] Global CCS Institute, Blue Hydrogen, Apr 2021, p.5-6.

[67] global CCS Institute, Global Status of CCS 2021, 2021, p.63-66.

[68] IEEFA, Blue Hydrogen: Technology Challenges, Weak Commercial Prospects, and Not Green, Schlissel, Wamsted, Feaster, Mattei, Mawji & Sanzillo, Feb 2022, p.15.

[69] Global CCS Institute, Global Status of CCS 2021, 2021, p63-66.

[70] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, Durrant & Kochhar, Oct 2021, p.96.

[71] Global CCS Institute, Global Status of CCS 2021, 2021, p.63-66.

[72] Global CCS Institute, Global Status of CCS 2021, 2021, p.59.

[73] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, Durrant & Kochhar, Oct 2021, p.99-100.

[74] Climeworks, Climeworks begins operations of Orca, the world's largest direct air capture and CO_2 storage plant, 8 Sep 2021.

[75] CISION, 1PointFive Selects Worley for FEED on Milestone Direct Air Capture Facility, 22 Feb 2021.

Technology Readiness

IRENA suggests that CCS is not an experimental technology, yet it is not yet widely deployed and has not performed as expected.[76] As IEEFA has discussed in a recent report[77], the contrasting views on maturity likely come from the maturity of different applications.

Technology Readiness Level (TRL)[78] is the framework used to consider where each application of CCS technology sits, with regards to technology readiness from concept to deployed extensively in an operational environment. There is fundamental uncertainty around TRL with all applications, in that public performance data is generally not available, and the storage of CO2 will need to be proved over millennia. This may raise questions about the real technological readiness level.

Figure 4: TRL Scale

TRL Score	Basic Description
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof of concept
4	Component and/or system validation in laboratory environment
5	Laboratory-scale, similar system validation in relevant environment
6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment
7	Full-scale, similar (prototypical) system demonstrated in relevant environment
8	Actual system completed and qualified through test and demonstration
9	Actual system operated over the full range of expected mission conditions

Source: ARENA 2019[79]

Note: Although widely used across energy technology, the limitations of this scale are that any technology that is deployed at commercial scale (i.e. a plant that is producing products for end-users) automatically gets a 7 regardless of performance. Accordingly, higher scores do not necessarily imply that the technology is viable.

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[76] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, Durrant & Kochhar, Oct 2021, p.10.
[77] IEEFA, Carbon Capture in the Southeast Asian Market Context, Putra Adhiguna, Apr 2022, p.2.
[78] ARENA, TRL Guide, 2019.
[79] ARENA, TRL Guide, 2019.

CCS for Gas Processing

CCS technology has been applied across gas processing since the 1970s, with a dozen facilities operational and more coming online. However, actual capture rates and performance are generally unknown. Recently, a major project – Project Gorgon in Australia – has faced many technical challenges in achieving its capture targets.[80] Its owner, Chevron, has been challenged getting this scale of project working and is only working half the time.[81] Given 40 plus years of experience, CCS projects in gas processing should technically be capable of capturing emissions. However, there are many instances where CO2 was vented when there was no demand for CO2 from EOR.[82] While IRENA[83] lists the TRL as fully mature (for EOR and saline formations), the inability to meet capture requirements on Project Gorgon casts doubt on the actual technology readiness.

CCS for Power

As mentioned in the previous section, two projects have been deployed in the operational environment. However, one of the facilities has suspended operation and both projects performed well below target capture rates of 90%.[84] CCS for power has several prototype-sized systems implemented, resulting in the IEA rating this application between 5 and 9, however it should be noted that observed issues and the high rate of facilitates that have failed to materialise[85] means they are not yet technologically proven[86].

CCS for Industrials

This category covers a wide range of industries, with some (i.e. ethanol and fertiliser) advanced and deployed widely, while others (cement and steel) are less demonstrated or established technically. The IEA has rated the TRL between 4-8 for cement, 6-8 steel and 9+ for ethanol and fertiliser.[87]

CCS for Blue Hydrogen

Blue hydrogen has been deployed across three commercially operational facilities, which is a relatively small scale compared to the size of the current traditional hydrogen production capacity. CCS for blue hydrogen has a few records of prototype-sized systems implemented, resulting in IRENA rating the application

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[80] IEEFA, Gorgon carbon capture and storage: the sting in the tail, Robertson & Mousavian, Apr 2022, p1-2.

[81] Reuters, Chevron says world's largest carbon capture project has 'a ways to go' to meet goals, 17 May 2022.

[82] IEEFA, Carbon Capture to Serve Enhanced Oil Recovery: Overpromise and Underperformance, Robertson & Mousavian, Mar 2022, p1-3.

[83] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, Durrant & Kochhar, Oct 2021, p.85

[84] IEEFA, Boundary Dam 3 Coal Plant Achieves Goal of Capturing 4 Million Metric Tons of CO2 But Reaches the Goal Two Years Late, David Schlissel, Apr 2021, p.1-3.

[85] Environmental Research Letters 16, Explaining successful and failed investments in U.S. carbon capture and storage using empirical and expert assessments, Ahmed Abdulla et al. 2021.

[86] IEA, CCUS in Clean Energy Transitions, Sep 2020, p.62, 99 - 100,

[87] IEA, CCUS in Clean Energy Transitions, Sep 2020, p.62, 98,

between 6 and 9[88], however as IEEFA have previously discussed the capture rates are well below the industry goal for 95% capture rate[89].

BECCS

There are a handful of pilot projects operating across a wide range of applications, including power and waste incineration[90] resulting in the Energy Transitions Commission (ETC) listing BECCS technology between 5 and 9 on the TRL scale[91].

DACCS

According to IRENA[92], DACCS is mainly at a small-scale demonstration stage with plans (and funding commitments) to scale the technology. Climeworks recently raised USD 650 million in an equity raise to support its scale-up of its DACCS technology[93] and Occidental plans to invest over USD 800 million in a DACCS project in the Permian Basin.[94] The ETC has listed the technology between 5 and 9 on the TRL scale.[95]

Commercial Readiness

Technical readiness does not indicate the success of the technology in the competitive marketplace. Emerging technologies will need to compete with incumbent technology and finance from risk-averse capital markets. Generally, emerging technologies will likely rely on government subsidies, thus lowering their commercial readiness to compete on their own in the marketplace. ARENA's CRI framework[96] does consider this in the ratings (as in Figure 6.). The robustness of the commercial readiness for each application has been qualitatively assessed against this framework.

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[88] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, Durrant & Kochhar, Oct 2021, p.79 .

[89] IEEFA, Blue Hydrogen: Technology Challenges, Weak Commercial Prospects, and Not Green, Schlissel, Wamsted, Feaster, Mattei, Mawji & Sanzillo, Feb 2022, p.18 .

[90] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, Durrant & Kochhar, Oct 2021, p.97.

[91] ETC, Mind The Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive, March 2022, p.38.

[92] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, Durrant & Kochhar, Oct 2021, p.15.

[93] Bloomberg, Climeworks Raises $650 Million in Largest Round for Carbon Removal Startup, 5 Apr 2022.

[94] Reuters, Occidental plans up to $1 bln for facility to capture carbon from air, 24 Mar 2022.

[95] ETC, Mind The Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive, March 2022, p.38.

[96] ARENA, Commercial Readiness Index for Renewable Energy Sectors, 2014.

Figure 5: CRI Scale

CRI Ring	Short Description
1	Hypothetical commercial proposition – commercially untested and unproven.
2	Commercial trial – funded by equity and government support.
3	Commercial scale up – driven by policy and emerging debt finance.
4	Multiple commercial applications – verifiable technical and financial data in the public domain may still be subsidised.
5	Market competition driving widespread deployment – commoditization of components and financial products occurring.
6	"Bankable" grade asset class – known standards and performance expectations.

Source: ARENA 2014[97]

Note: Even commercial projects with high subsidies would score a 2 regardless of commercial competitiveness.

CCS for Gas Processing

Given the number of facilities and the length of operations, CCS for gas processing appears to be a bankable asset class with the appropriate revenues in place (either via investment tax credit or EOR offtake). However, issues with project venting and the technical failure of some projects to deliver permanent storage[98] may raise the bankability of this application with some lenders. This is due to emerging conditions placed on lending to the applications, due to the environmental and social impacts (and opposition[99]) of supporting more fossil-fuel extraction (and oil and gas companies in general). Additionally, given the lack of verifiable technical and financial data, the CCS for gas processing would score in the mid-ranges for commercial readiness.

CCS for Power

Enel's CEO has raised scepticism about whether CCS for power is reliable technically or commercially.[100] With only one commercially operating plant, and one recently closed due to being uneconomic due to low oil prices[101], the commercial readiness of CCS for power seems low. Recent global energy market conditions with high oil and gas prices will help push the commercial attractiveness of CCS associated with EOR. However, what oil and gas prices do over the longer term is unclear and will be part

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[97] ibid.

[98] IEEFA, Carbon Capture to Serve Enhanced Oil Recovery: Overpromise and Underperformance, Robertson & Mousavian, Mar 2022, p1-3.

[99] Financial Post, More than 400 academics urge Canada to ditch carbon capture tax credit, 20 Jan 2022.

[100] CNBC, For us, it is not a solution': Enel CEO skeptical over the use of carbon capture, 25 Nov 2021.

[101] IEEFA, Boundary Dam 3 Coal Plant Achieves Goal of Capturing 4 Million Metric Tons of CO_2 But Reaches the Goal Two Years Late, David Schlissel, Apr 2021, p.1.

of investment decision-making. There are many large (3 - 6 Mtpa of CO2) facilities in development, although at least one of these appears to be facing investment challenges.[102] Considering the challenges, based on the balance of the evidence, it is likely the application would be scored low on the scale.

CCS for Industrials

Again, CCS for industrials covers a broad range of technologies that have deployed successfully in ethanol and fertiliser applications, to applications that are very commercially immature (i.e. steel and cement). The one commercial-scale steel project is largely commercially viable due to its association with EOR.[103] BNEF notes that access to and costs of transport and storage are a limiting factor for CCS commerciality, which may be beyond the individual project operators and will benefit from shared transport and storage schemes.[104] CCS in industrial applications has a range of different readiness levels, but is unlikely bankable.

CCS for Blue Hydrogen

There are only two blue hydrogen production facilities operating globally at a significant scale (i.e. greater than 1 Mtpa) and these are heavily (two-thirds) subsidised by government grants and lending.[105] At least four facilities are being developed and expected to be online in the next five years. This application would likely score relatively low on commercial readiness.

BECCS

CCS technology has only been applied in ethanol production from biomass, which is a very different application for the power sector and heavy industrial applications (where BECCS is hoped to have a significant impact). According to IRENA[106], the technology has shown promising economics across various applications (including power plants with co-firing). However, the technology is only operating at pilot in these industries. BECCS is likely at the commercial stage.

DACCS

With the DACCS technology operating in a handful of small-scale operations, but having recently attracted significant equity investment into projects, the projects would be considered at the lower end of the CRI scale.

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[102] IEEFA, Enchant's San Juan Generating Station CCS Retrofit Remains Behind Schedule, Financially Unviable, David Schlissel, May 2021, p.1.

[103] The National News, Abu Dhabi starts up world's first commercial steel carbon capture project, 5 Nov 2016.

[104] BloombergNEF, Decarbonizing Steel: Technologies and Costs, 25 Aug 2021, p.22.

[105] IEEFA, Blue Hydrogen: Technology Challenges, Weak Commercial Prospects, and Not Green, Schlissel, Wamsted, Feaster, Mattei, Mawji & Sanzillo, Feb 2022, p.25

[106] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, Durrant & Kochhar, Oct 2021, p.12.

Marginal Abatement Cost Competitiveness

In the context of climate change, the marginal abatement cost (MAC) is the cost of a technology to reduce pollution by a tonne of CO2 ($/t-CO2). MAC measures the cost effectiveness of each technology to decarbonise, rather than the cost competitiveness of the process to produce its primary output (power, steel, cement, etc.). Technologies with lower MACs are generally considered higher priority due to their ability to reduce emissions cheaply. A negative abatement cost shows that there is an opportunity to reduce costs while also reducing emissions.

The MACs vary by application and are most influenced by the concentration of CO2, capture technology, plant size, process design, plant utilisation, location, type of transportation, type of storage, cost of capital[107] and revenues available. Costs will generally be greater for low CO2 concentration projects.[108] Transport and storage costs depend on site specifics, such as distance, type of storage, and monitoring and verification costs to comply with local regulations. Revenue streams for utilisation (such as EOR) or revenue from carbon pricing, grants or tax incentives will generally be required to make CCS technologies economic and make MACs more competitive with alternative abatement options.

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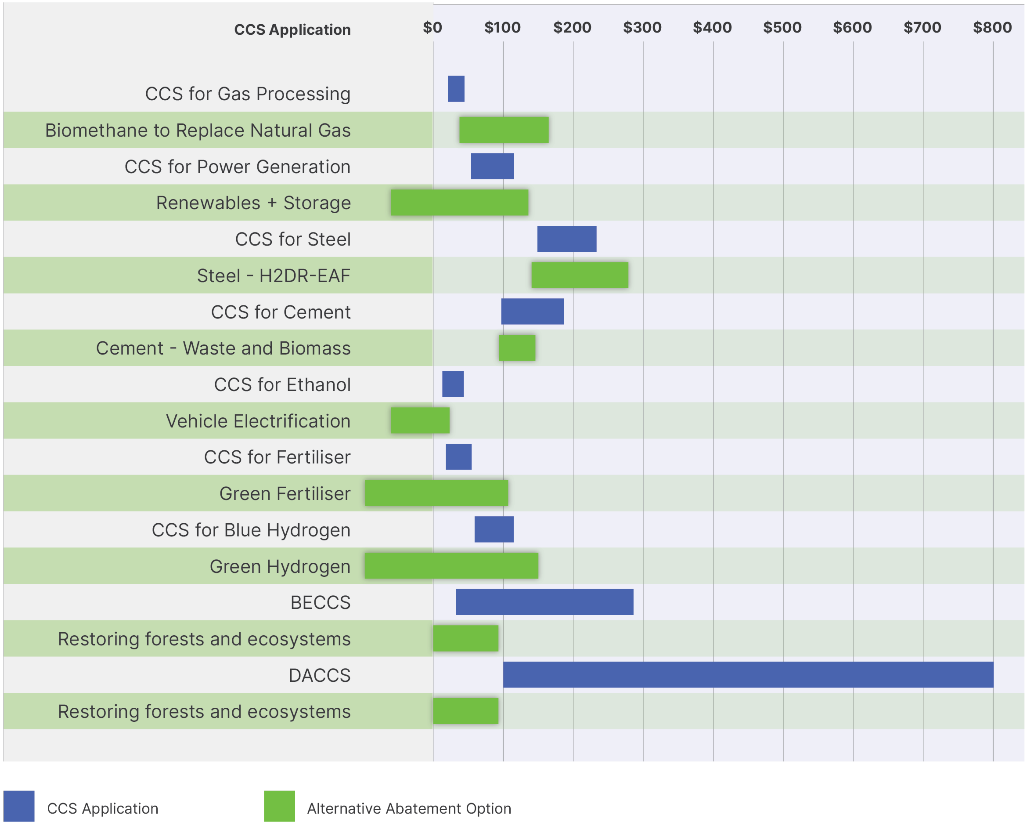
[107] S&P Global Levelized cost of CO2 avoided (LCCA) for CCUS projects - Cost drivers and long-term cost outlooks, 3 May 2022.

[108] ibid.

Figure 6. Most CCS applications are not cost competitive as decarbonisation pathways

Current estimates of CCS for gas processing and some industrial applications may provide cost-competitive abatement pathways. Other CCS applications are not cost-competitive as decarbonisation pathways.



Source: Author's analysis based on BNEF, ETC, Evolved Energy Research, Forbes, Global CCS Institute, Goldman Sachs Research, IEA, IEEFA own research, IPCC, IRENA, Lazard, PNAS, Royal Society of Chemistry, National Energy Technology Laboratory[109]

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[109] BloombergNEF, Decarbonizing Steel: Technologies and Costs, 25 Aug 2021.
ETC, Mind The Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive, March 2022, p.38.
Evolved Energy Research, Marginal Abatement Cost Curves for U.S. Net-Zero Energy Systems, August 2021, p.5.
Forbes, Estimating The Carbon Footprint Of Hydrogen Production, 6 Jan 2020.
Global CCS institute, Is CCS Expensive?: Decarbonisation costs in the net-zero context, May 2020.
Goldman Sachs Research, Carbonomics: The Future of Energy in the Age of Climate Change, 11 Dec 2019, p.38.
Goldman Sachs Research, Carbonomics: The Future of Energy in the Age of Climate Change, 11 Dec 2019, p.39. - Assumed high gas price case, base case scenario for solar / wind and batteries.
IEA, Global marginal abatement costs for biomethane to replace natural gas, with and without credit for avoided methane emissions, 2018, p.80.
IEA, Abatement costs for road vehicles, 7 Oct 2021 - BEV and electric buses at USD 60 barrel of oil.
IEEFA, Blue Hydrogen: Technology Challenges, Weak Commercial Prospects, and Not Green,

Notes: Negative abatement costs show there is opportunity to reduce costs while also reducing emissions.
MACs are estimates from techno-economic studies from a range of sources, but the true MACs are unable to be verified or validated. Early experience with CCS for power110 111 indicates projects typically take longer; costs more to build than originally claimed; and typically experience technical and efficiency problems.
The large range for green hydrogen represents the effect of recent commodity price increases that have increased the costs of the unabated fossil-fuel hydrogen production pathway.
MACs for blue hydrogen, BECCs and DACCS may not include transport and storage. Transport and storage costs vary depending on the distance, transport, and size and type of storage. Transport costs can vary between $1 - 15 / t-CO2 and storage costs can vary between $1 - 25 t/ CO2.112

CCS applied to gas processing has a low MAC and is more attractive than current alternatives to reduce gas emissions. Industrial applications and BECCS are no more competitive than alternatives. The economics of blue hydrogen, compared with green hydrogen, have recently become far less attractive due to high commodity prices. Low and mid-cost renewables with storage provide more attractive MACs than CCS for power generation. However, in some contexts (such as those with low renewable resource availability, high renewable system costs and low marginal cost thermal generators) the cost of renewables may be less competitive than CCS applications.

DACCS is currently not competitive with alternatives. Natural climate solutions, including afforestation, ecosystem restoration and soil carbon sequestration, provide attractive alternative mitigation options to BECCS and DACCS. These solutions can deliver improved outcomes for biodiversity, water supply, food security, and income to local communities. However, it faces unique competing land use and permanence of sequestration challenges.[113]

Schlissel, Wamsted, Feaster, Mattei, Mawji & Sanzillo, Feb 2022, p.26.
IPCC Sixth Assessment Report Climate Change 2022: Mitigation of Climate Change, April 2022, p.37.
IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, Durrant & Kochhar, Oct 2021, p.95-99
Lazard, Lazard’s Levelised Cost of Hydrogen Analysis, June 2021 p.12.
PNAS vol.115, Infrastructure to enable deployment of carbon capture, utilization, and storage in the United States. Edwards & Celia. 4 Sep 2018. P.8816.
Royal Society of Chemistry, Direct air capture: process technology, techno-economic and socio-political challenges, Erans et al., 28 Feb 2022.
National Energy Technology Laboratory, Bituminous Coal and Natural Gas to Electricity: >90% Capture Cases Technical Note, Travis Schulz, 30 Dec 2021.

[110] IEEFA, Holy Grail of Carbon Capture Continues to Elude Coal Industry, Schlissel & Wamsted, Nov 2018. p.2-14.

[111] IEEFA, Boundary Dam 3 Coal Plant Achieves Goal of Capturing 4 Million Metric Tons of CO2 But Reaches the Goal Two Years Late, David Schlissel, Apr 2021, p.1-3.

[112] The Royal Society, Total cost of carbon capture and storage implemented at a regional scale: northeastern and midwestern United States, Schmelz, Hochman & Miller,14 Aug 2020, p4-6.

[113] ETC, Mind The Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive, March 2022, p.38&58.

Given the generally low level of commercial readiness across most CCS applications, lower MACs can be achieved only if there are economies of scale, process improvements, and increased competition between providers.[114]

Environmental Credibility

Based on IEEFA's previous analysis of actual and proposed CCS projects, general environmental issues raised with CCS include: the continued use of fossil fuels, ability to live up to its claims for emissions reductions, uncertainty and risk around the long-term storage and leakage of CO2, increased energy use (and resultant extraction and emissions) from the decrease in efficiency from adding CCS to processes, harmful chemicals used in the CCS technology, water usage and lifecycle emissions impact. These issues will be different for each application and the national and geographical context in which they operate.

Regarding storage, IRENA[115] notes that saline formations and EOR have been carried out for decades without major issues, but the scale has been small in relation to what is needed. More work is needed to ensure the integrity of transport and permanence of storage, as a very large release of CO2 from a large-scale operation has consequences that could be severe for both humans[116], the environment[117], and the net-zero scorecard. Monitoring and verification processes will be a critical part of any storage project to ensure the permanence of storage. The credibility of storage will also depend on the monitoring and verification practices in different jurisdictions. Insurance on the risk of leakage in the form of buffer-credits.[118]

There are particular environmental issues to consider across the various applications.

CCS for Gas Processing

The majority of CO2 currently captured is used with EOR to extract more oil out of depleted fields rather than curbing huge amounts of CO2 emissions.[119] Additionally, CCS facilities often choose to sell or vent CO2 depending on oil prices.[120] This puts CCS for gas processing with EOR at odds with efforts to eliminate global emissions. However, gas processing should aim to reduce all emissions, including capturing and permanently storing CO2 from processing. With energy security an increasing problem and countries looking to secure supply chains and strategies that may

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[114] DNV, Energy Transition Outlook 2021: Technology Progress Report, 62-65.

[115] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, M., P. Durrant & K. Kochhar, October 2021, p.24.

[116] HuffPost, The Gassing Of Satartia, 26 Aug 2021

[117] Energy Procedia, Volume 114, Integrated Sustainability Assessment of CCS – Identifying Non-technical Barriers and Drivers for CCS Implementation in Finland, Pihkola et al., 2017, p.7625-7637.

[118] ETC, Mind The Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive, March 2022, p.63.

[119] IEEFA, Carbon Capture to Serve Enhanced Oil Recovery: Overpromise and Underperformance, Robertson & Mousavian, Mar 2022, p1-3.

[120] ibid.

involve new gas extraction, gas processing with CCS (and proven permanent storage) will be a better alternative than EOR or no CCS at all.

CCS for Power

CCS for power, and the other environmental risks discussed above, have a major energy penalty. This penalty is the consumption of additional energy to capture the CO2 from flue gas. CCS may consume up to 20-30% of the power generated, resulting in a net efficiency reduction of 6 to 12 percentage points should be expected [121] [122]. This means additional energy is used (and fossil fuels extracted, transported, and burnt) when CCS is applied to generate the same amount of power. Additionally, CCS with power plants will consume around 50% more water than non-CCS plants per megawatt (MW) of capacity.[123]

Life cycle assessment studies have suggested that CCS should generally cut a facility's CO2 emissions, and in some cases, may reduce SOx and NOx emissions[124], which is expected to have a positive environmental impact.[125] However, when the impacts due to the increasing need for fuels and transports are considered, upstream and downstream lifecycle emissions may increase depending on the technology used.[126] Additionally, large quantities of ammonia, hydrogen sulphide and other chemical solvents are needed, which has the potential for harm to the environment, if a spill were to occur.

CCS for Industrials

While CCS for industrials have similar environmental issues to other CCS applications, there are possible emission benefits to consider. Steel and cement industries account for around 8% of global emissions[127] [128]. Steel with CCS is a decarbonisation pathway being considered to develop low carbon steel. Using scrap metal and green hydrogen are promising alternatives.[129] However, there are unique challenges with scaling each of the pathways[130]. The final pathway for steel is still

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[121] National Energy Technology Laboratory, Bituminous Coal and Natural Gas to Electricity: >90% Capture Cases Technical Note, Travis Schulz, 30 Dec 2021, p.4.

[122] IEEFA, Carbon Capture in the Southeast Asian Market Context, Putra Adhiguna, Apr 2022, p.34.

[123] National Energy Technology Laboratory, Bituminous Coal and Natural Gas to Electricity: >90% Capture Cases Technical Note, Travis Schulz, 30 Dec 2021, p.3.

[124] European Environment Agency (EEA), EEA Technical report: Air pollution impacts from carbon capture and storage (CCS), 2011.

[125] Energy Procedia, Volume 114, Integrated Sustainability Assessment of CCS – Identifying Non-technical Barriers and Drivers for CCS Implementation in Finland, Pihkola et al., 2017, p.7625-7637.

[126] Journal of CO2 Utilization Vol.9. Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts Cuéllar-Franca & Azapagic. 19 Dec 2014. p.90.

[127] Leadership Group for Industry Transition (LeadIT), Green steel production: How G7 countries can help change the global landscape, 10 Jun 2021.

[128] Beyond Zero Emissions (BZE), Rethinking Cement: Australia can have a zero carbon cement industry in 10 years, 2017.

[129] IEEFA, New From Old: The Global Potential for More Scrap Steel Recycling, Nicholas and Basirat, Dec 2021, p.1-3.

[130] AIGCC, Carbon Capture and Storage in the decisive decade for decarbonisation: The case for Asia, Mar 2022, p.21.

yet to be determined, but we note there are no plans for any major industrial-scale CCS for steel in the pipeline and an increasing number of plans for green steel through green hydrogen.[131] CCS technology provides the only current viable option to eliminate emissions for the calcination process (accounting for around 50% of emissions) in the cement industry, which will (quite literally) provide the footing for massive renewables growth.

CCS for Blue Hydrogen

Blue hydrogen, which inherently includes CCS, has received a lot of controversy as a shade of 'greenwashing' and its association with its clean cousin green hydrogen (hydrogen produced via electrolysis using renewable electricity). Particularly, issues have been raised about the lifecycle emissions of blue hydrogen production. Recent analysis suggests it could be 20% worse than using gas due to the fugitive methane emissions released during the extraction phase of the supply chain.[132]

BECCS

While BECCS provides a pathway to negative carbon emissions under the right conditions, there are some environmental issues to consider. Along with the common problems associated with CCS technology, BECCS technology faces the environmental issues raised with all bioenergy projects. Particularly, concerns are raised about the sustainability of biomass sources, land-use change and deforestation. Biomass can only be considered carbon neutral if the biomass is continually renewed and the cultivation does not cause other negative land use changes.[133] Therefore, careful management and governance of BECCS supply chains will be necessary for the technology to be considered part of the net-zero toolkit. Additionally, BECCS has the highest water usage requirements of carbon capture technologies required for the growth of biomass feedstocks.[134] If these issues can be managed and BECCS can be commercially scaled, BECCS may provide a viable pathway for negative emissions.

DACCS

DACCS technology also provides promise, but the issues around the chemicals used in capturing carbon, also have an energy challenge. Current DAC technology requires about 2 MWh per tonne of CO2 captured.[135] If this number is accurate to current DAC technology, then global electricity demand could increase global energy

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[131] Agora Industry,Wuppertal Institute and Lund University. Global Steel at a Crossroads: Why the global steel sector needs to invest in climate-neutral technologies in the 2020s, 2021, p.3.

[132] Energy Science and Engineering, How green is blue hydrogen?, Howarth & Jacobson, 12 Aug 2021.

[133] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, Durrant & Kochhar, Oct 2021, p.18.

[134] Renewable and Sustainable Energy Reviews Vol. 138, The water footprint of carbon capture and storage technologies, Rosa et al. 2021.

[135] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, Durrant & Kochhar, Oct 2021, p.99.

by around 1 - 1.6% for each Gt of CO2.[136] If the energy is powered by renewables then there isn't an increase in CO2. However, if powered by current grids, the emissions from electricity generation could be 1.5 times the CO2 captured.[137] Clearly, DACCS will only be part of the decarbonisation toolkit if powered by renewables and efficiency gains are made.

Social Credibility

The most important social impact is the potential reduction in emissions to deliver a more sustainable planet for future generations, however, there are other social impacts to consider. Developing any large-scale infrastructure often faces opposition from local communities. Accordingly, the development of CCS infrastructure, including pipeline and storage, is likely to trigger similar resistance in adjacent communities. Additionally, false plans to deploy CCS and failures of facilities to capture the agreed levels of CO2 erode public trust in CCS technology. The hazard and safety of materials in the technology and chemicals used may also provide a source of social opposition.

There are particular social issues to consider within each of the applications.

CCS for Gas Processing

There is concern about the risks of continuing to support fossil fuel extraction as we try to achieve net-zero. Oil and gas companies are seen as (and some regions still are) massive beneficiaries of government funding. Additionally, windfall profits with recent surging energy prices[138] mean there is little justification that these companies deserve any more funding support to underpin operations. Any CCS project associated with the oil and gas sectors is likely to continue to receive public opposition.

CCS for Power

As with its fossil-fuel companions in the oil and gas sectors, coal and gas generators assets lie on the energy transition tracks. The negative aura around these companies is not without cause. They have traditionally benefited from government subsidies and protectionist policies to maintain their market position. They have also often danced around environmental and social responsibilities and regulations. CCS for power generation is likely to face organised public opposition and tougher environmental regulations.[139]

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[136] IRENA, Reaching Zero with Renewables: Capturing Carbon, Lyons, M., P. Durrant & K. Kochhar, October 2021, p.99.

[137] Calculated using Australia's National Electricity Market emissions factor from Australian Government, National Greenhouse Account Factors, Aug 2021, p.20.

[138] CNBC, Oil major TotalEnergies swings to profit thanks to surging commodity prices, 10 Feb 2022.

[139] IEEFA, Where's the Beef?:Enchant's San Juan Generating Station CCS Retrofit Remains Behind Schedule, Financially Unviable, David Schlissel, May 2021, p.2.

There is an argument that CCS in power generation can help reduce stranded assets and associated capital destruction. McKinsey's analysis suggests that around $2.1 trillion of assets in the global electricity sector could be stranded by 2050.[140] This level of stranded assets will create economic losses that will distribute winners and losers across different geographies.[141] This may be less severe than the penalties that climate change imposes.[142] An alternative view is that if CCS fails to work, investing in CCS will actually increase the value of stranded assets. In any case, each actor is likely to pursue an outcome that maximises their chances of survival.

CCS for Industrials

CCS in industrial applications can help industrial sectors decarbonise and remain operating in a net-zero world. This can support industries and workers and continue the societal benefits that flow from industrial applications, including producing clean energy technology using low-carbon processes.

CCS for Blue Hydrogen

Despite the environmental issues of blue hydrogen, there is a social argument to consider. Proponents argue that blue hydrogen can provide a useful stepping stone to green hydrogen by utilising gas sector expertise to deploy hydrogen technology. This helps develop global supply chains and demand, while green hydrogen comes to scale and increases cost competitiveness. However, with current high commodity prices, green hydrogen is already outcompeting blue hydrogen, while in other markets (i.e. Europe) green hydrogen is not expected to be competitive until the 2030s.[143] The problem then is remaining locked into the facilities and technology once built.

BECCS

The social issues around BECCS are strongly tied to environmental issues. This has to do with the sustainability and impacts of the biomass used in the processes. Crops produced for energy compete with other land uses such as food production and forests, which have critical social usefulness and deep ecological value. If crops can be produced in a way that is not competing with these land uses and does not lead to land use change, or biomass residues are used, then BECCS could, on balance, have a positive social impact due to its ability to provide negative emissions. The Energy Transition Commission (ETC) sees 170 facilities capturing a total of 200 Mtpa are required by 2030.[144]

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[140] McKinsey, McKinsey Quarterly: Playing offense to create value in the net-zero transition, 13 Apr 2022.

[141] Nature Clim Change 8, Macroeconomic impact of stranded fossil fuel assets, Mercure, JF., Pollitt, H., Viñuales, J.E. et al., 2018, p.588–593.

[142] Annual Review of Environment and Resources, Stranded Assets: Environmental Drivers, Societal Challenges,and Supervisory Responses. Caldecott et al. 23 Aug 2021.

[143] Recharge News, Green hydrogen now cheaper than blue in Middle East, but still way more expensive in Europe, 24 Feb 2022.

[144] ETC, Mind The Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive, March 2022, p.13.

DACCS

There is concern for 'Moral Hazard' with DACCS technology, and that relying on it will introduce risks borne by all. Some see it provides a mythical "silver bullet" to climate mitigation and will delay action. However, as many credible organisations have pointed out, it is likely that the carbon budget is not on track for 1.5C and will likely be overshot, and CDR is absolutely needed. As the ETC suggests, 80 facilities capturing a total of 100 Mtpa are needed by 2030.[145]

Conclusion

Overall, carbon capture technologies are not yet ready to warrant them investable. A key impediment to investment is the lack of available and weak quality data from the testing and operations of CCS across all applications, which makes the real technology, commercial readiness, costs and cost competitiveness uncertain.

CCS for Gas Processing has been thought to be well-advanced technologically and commercially and is thus currently the primary CCS technology in the market. However, we note there is limited publicly available information to scrutinise across all operational projects. Additionally, CCS for gas processing faces the greatest environmental and social challenges.

CCS for Power is one of the new use cases being discussed as a net-zero energy solution but has been challenged in meeting performance targets. The technology is also not commercially advanced and faces cost competitiveness challenges against alternatives like renewables and storage as a climate change mitigation option for the power sector. It also faces similar social and environmental challenges and lacks transparency of verified project data similar to CCS for gas processing.

CCS for Industrials (Steel and Cement) is overall not well-advanced, but if proven to be technically and commercially robust, it does offer potential as a viable decarbonisation option in these hard to abate sectors. However, with no plans for any major industrial-scale CCS for steel and an increasing number of plans for green steel through green hydrogen[146], the usefulness of CCS for steel is still an open question. In some contexts, it may still prove a useful option in steel and is the only viable, scalable pathway for cement process emissions. Therefore, CCS may provide more environmental and social usefulness in these applications.

CCS for Industrials (Ethanol and Fertiliser) is thought to be well-advanced technically and commercially. There is a long list of ethanol projects in advanced development stages globally. Recent surging gas prices have meant green hydrogen pathways (such as green fertiliser) are becoming increasingly cost-competitive. Regardless, capturing CO2 emissions for industrial processes should generally be a positive outcome for society and the environment.

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[145] ibid.

[146] Agora Industry, Wuppertal Institute and Lund University. Global Steel at a Crossroads: Why the global steel sector needs to invest in climate-neutral technologies in the 2020s, 2021, p.3.

CCS for Blue Hydrogen has performance issues, is not very well advanced commercially and has low adoption. The environmental issues with the technology are of real concern, as recent analysis has shown it may increase emissions while claiming to be a clean energy vector.

BECCS and **DACCS** are not well advanced technically or commercially but offer significant environmental and social usefulness should they prove commercially robust technologies.

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