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REACHING ZERO WITH RENEWABLES
CAPTURING CARBON

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The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation, a centre of excellence, a repository of policy, technology, resource and financial knowledge, and a driver of action on the ground to advance the transformation of the global energy system. An intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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REACHING ZERO WITH RENEWABLES

CAPTURING CARBON

The status and potential of carbon capture and storage (CCS), carbon capture and utilisation (CCU) and carbon dioxide removal (CDR) technologies, and their synergies with renewables in the context of global pathways to net-zero emissions.

CONTENTS

FIGURES

TABLES

BOXES

ABBREVIATIONS

AMP	amino-methyl-propanol
ATR	auto thermal reforming
BECCS	bioenergy with carbon capture and storage
BF-BOF	blast furnace–basic oxygen furnace
°C	degrees Celsius
CaO	calcium oxide
CAPEX	capital expenditures
CCGT	combined cycle gas turbines
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CDR	carbon dioxide removal
CO_2	carbon dioxide
CO_{2eq}	carbon dioxide equivalent
CS	crude steel
DAC	direct air (carbon) capture
DACCS	direct air (carbon) capture and storage
DACCU	direct air (carbon) capture and utilisation
DRI	direct reduced iron
EAF	electric arc furnace
ECRA	European Cement Research Academy
EIB	European Investment Bank
EJ	exajoule
EOR	enhanced oil recovery
EU	European Union
FOAK	first-of-a-kind
Gt	gigatonnes
Gtpa	gigatonnes per year
GW	gigawatt
H2	hydrogen
HRC	hot rolled coil
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ktpa	kilotonnes per year
kWh	kilowatt hour
kWhe	kilowatt hours electric
LCOE	levelised costs of electricity
LEDS	low-greenhouse-gas emission development strategies
LULUCF	land use, land-use change, and forestry
MEA	monoethanolamine
MDEA	methyldiethanolamin
MJ	megajoule
MSW	municipal solid waste
Mtpa	megatonnes per year
MW	megawatt
MWh	megawatt hour
N	nitrogen
Nm_3	normal cubic metre
NDC	Nationally Determined Contributions
NGCC	natural gas combined cycle
NOx	nitrogen oxides
NO_2	nitrogen dioxide
O&M	operation and maintenance
OPEX	operating expenditures
PCC	post-combustion capture
PCI	Project of Common Interest
PPA	power purchase agreement
ppm	parts per million
Pz	piperazine
RD&D	Research, development and demonstration
SO_2	sulphur dioxide
SMR	steam methane reforming
T&S	transport and storage
tCO_2	tonne of CO_2
TGR-BF	top gas recycled blast furnace
toe	tonne of oil equivalent
Tpa	tonnes per year
TRL	technology readiness level
TWh	terawatt hour
UK	United Kingdom of Great Britain and Northern Ireland
UNFCCC	United Nations Framework Conventions on Climate Change
USC	ultra-supercritical

EXECUTIVE SUMMARY

This technical paper explores the status and potential of carbon capture and storage (CCS), carbon capture and utilisation (CCU) and carbon dioxide removal (CDR) technologies and their roles alongside renewables in the deep decarbonisation of energy systems. It complements and builds upon the broader discussions on the energy transition in other recent IRENA reports, including the *World Energy Transitions Outlook* (IRENA, 2021a) and *Reaching Zero with Renewables* (IRENA, 2020). The paper summarises the status of these technologies in terms of current deployment and costs, potential future roles, and the challenges and prospects for scaling-up their use in the context of the 1.5°C climate change goal and achieving net-zero emissions by 2050. The main report provides an overview of these topics whilst the annexes provide additional resources and more detailed background information, including a discussion of key components, and tables presenting information on existing and planned projects.

The capture and storage of CO_2 has a moderate but indispensable role to play in global deep decarbonisation strategies; but the pace of recent progress in validating and deploying CCS, CCU and CDR technologies in multiple sectors falls far short of pathways consistent with the 1.5ºC goal.

The role of different CO_2 capture technologies is a sometimes contentious and often poorly understood component of the energy transition. Technologies for capturing carbon should not be a tool for propping up the weak business case for continued fossil fuel use but they do have a role in addressing aspects of emissions reduction that other technologies cannot. In many applications there are better choices – such as the use of renewables in the power sector – but in some industrial sectors, and for balancing emissions at the system level, the capture and storage of CO_2 is important.

The pace of progress in CO_2 capture has been slow to date, and whilst there are some signs that this may change, the sector is starting from a low base and, given the long project leads times for capture, transport and storage infrastructure, it will take many years for CO_2 capture to begin to have a notable impact on emissions.

The lack of momentum in scaling deployment, building confidence and reducing costs poses a major risk to global emissions reductions. In the context of 1.5°C pathways, enhancing the collective understanding of the issues, and building consensus around realistic CO_2 capture pathways and the actions needed to address the slow pace of scale-up is now critical.

Key messages in the briefing include:

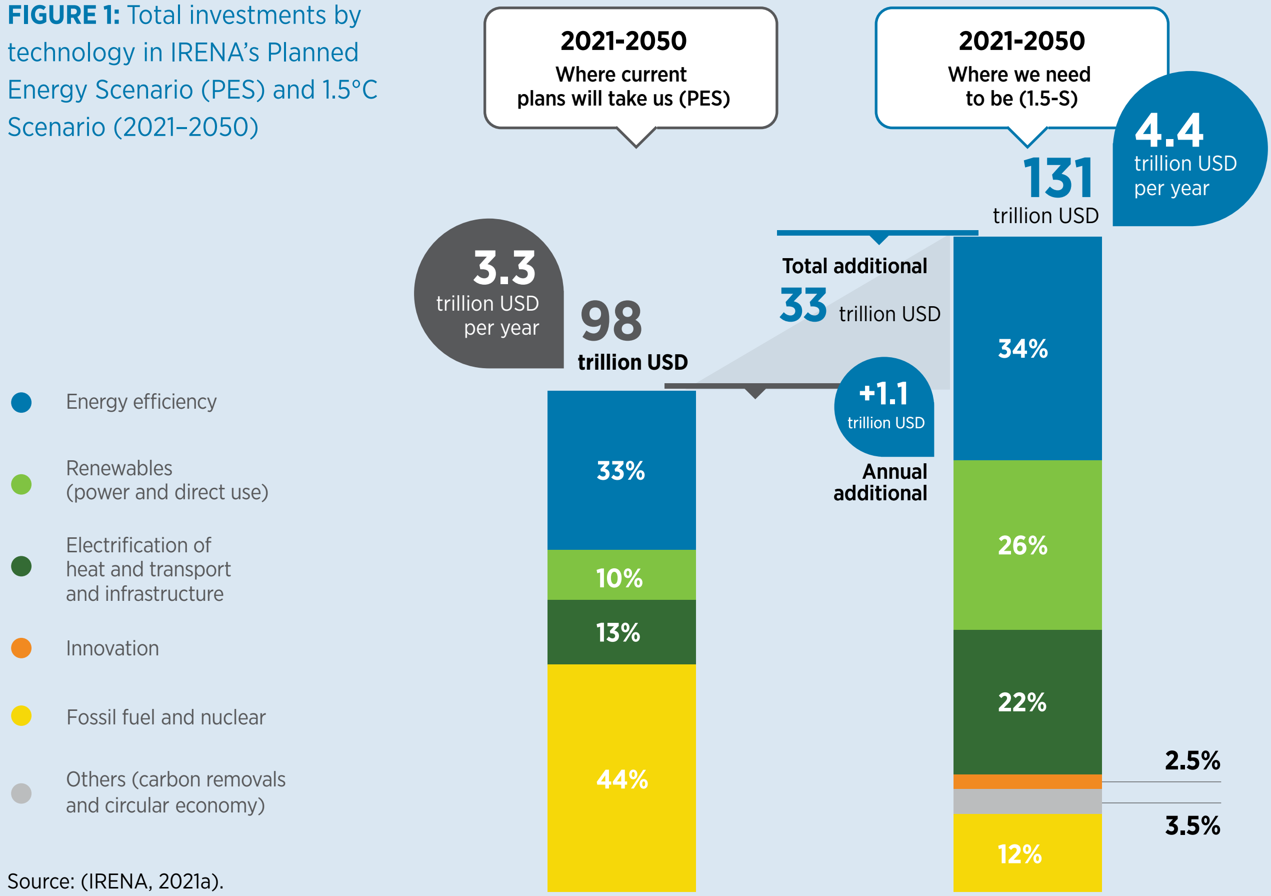
Capturing carbon for the energy transition

- Reaching net-zero by 2050 will require every tool in the decarbonisation toolbox. CO_2 capture solutions are a necessary component, particularly for the cement, steel and chemical industries, and to deliver negative emissions, but progress is well off the pace needed.
- The terms CCS, CCU and CDR are often conflated with CCUS or CCU/S (carbon capture, use and storage), which are often unhelpfully used as shorthand for CCS and CCU, and sometimes for all three. In the context of the need for deep decarbonisation and in particular the net-zero goal, however, it is very important to distinguish between them. They share some common elements but their roles and their impacts on net emissions of CO_2 vary in terms of their ability to reduce or remove CO_2.
- CCS refers to processes that directly capture CO_2 emissions from "point sources", i.e. from fossil fuel use or industrial processes, with the CO_2 subsequently being stored for a long period.
- CCU refers to processes that after capture, utilise the CO_2 in secondary processes such as synthetic fuels, chemicals and materials.
- CDR, by contrast, refers to processes that remove CO_2 from the atmosphere instead of simply reducing what is added/emitted, and if combined with long-term storage can result in negative emissions.
- Distinctions need to be made between the roles and system values of CCS, CCU and CDR. The total impact on atmospheric CO_2 concentration in the next few decades is the key criterion; while CCS and CCU technologies can "reduce" adding additional CO_2 to the atmosphere, CDR technologies actually "remove" CO_2 emissions from the atmosphere.

Fossil fuel CCS vs. renewables

- The use of renewables coupled with reductions in energy intensity will be the principal pillars of a net-zero pathway, but they will need to be supplemented in some contexts by CO_2 capture and storage.
- In the power sector, renewables outcompete fossil fuels with CCS in terms of levelised costs of electricity (LCOE) and, in contrast to renewables, no significant capacity has been built to-date. CCS for fossil fuel-based power production is not economically justifiable for new projects and the financial case for retrofit appears marginal.
- In industrial sectors, CCS and renewables are more complementary. Hydrogen, ammonia and methanol production from fossil fuels with CCS, and iron and steel production from fossil fuels with CCS, are currently marginally cheaper per unit of CO_2 removed than renewable options, although the cost gap is likely to close this decade. CCS-based projects, however, are currently more complex to finance and build than renewables, typically have lead times of 5–10 years, and still result in GHG emissions. The clearest case for CCS is in cement production, where renewable fuels cannot address process emissions.
- IRENA's 1.5°C Scenario assesses that global CO_2 capture and storage rates should reach round 6 gigatonnes per annum (Gtpa) of CO_2 by 2040 and over 8 Gtpa by 2050, from a current rate of 0.04 Gtpa (IRENA, 2021a). The scale of that ambition is vast:
  - The amount of CO_2 that would need to be permanently stored per annum in 2050 is approximately equivalent to the net amount of CO_2 currently captured per annum by the world's forests.
  - The volume of CO_2 that would need to be sequestered underground in 2050 is about 2.5 times the volume of oil being extracted per annum today.

FIGURE 1: Total investments by technology in IRENA's Planned Energy Scenario (PES) and 1.5°C Scenario (2021–2050)



Source: (IRENA, 2021a).

Reducing emissions: CCS and CCU status and potential

- Capturing carbon is not an experimental technology but nor is it yet widely deployed. The 24 commercial-scale fossil fuel-based CCS and CCU facilities in operation globally can capture only 0.04 Gtpa of CO_2 emissions and many have not performed as expected.
- Transportation options for CO_2 are technologically proven, but their scale remains limited. Geological storage of CO_2 in enhanced oil recovery (EOR) has been carried out for many years without major issues, all be it at comparatively small scales, and there is more than 12 000 Gt of potential CO_2 storage resources in saline formations, as well as other options (OGCI, 2020). But only c. 15.6 million tonnes per year (Mtpa) of CO_2 additional storage capacity was added in the last nine years and long-term liability issues remain unaddressed.
- Utilisation has a role but, in the medium and long terms, it should be limited to applications that do not lead to the later release of the CO_2. In the near term, during the scale-up of carbon capture deployment, uses that release CO_2 may be justified as interim measures. Potential uses include synthetic fuels, mineralisation for building materials, and the production of urea, methanol and other chemicals.
- Carbon capture from fossil fuel use and industrial processes must be aggressively scaled up to reach around 3.4 Gtpa of CO_2 by 2050 from the current 0.04 Gtpa. 30 projects are in development, adding 0.06 Gtpa of CO_2 capture potential, but a 1.5°C-consistent pathway could require between 1 Gtpa and 2 Gtpa of CO_2 captured

by 2030. Delivering c. 2 Gtpa of CO_2 capture and storage by 2030 would require cumulative investments of the order of USD 0.4 trillion by 2030, while capturing 8.5 Gtpa of CO_2 by 2050 would require close to USD 2 trillion by 2050 (Figure 1) (IRENA, 2021a).

- The views on the future role and scale of CCS and technological[1] CDR vary in the net-zero strategies and pathways of respected organisations and national governments. The SR1.5 report (2018) of the Intergovernmental Panel on Climate Change (IPCC) suggested CCS and technological CDR of over 20 Gtpa of CO_2 by 2050, while the International Energy Agency's (IEA) Net Zero Emission scenario (2021) and IRENA's 1.5°C Scenarios (2021) envisage total CO_2 capture through CCS and technological CDR at roughly a third of that level – in the range of 7–8 Gtpa of CO_2 (Gielen et al., 2021). The IPCC SR1.5 report, however, is based on older literature that underestimated the rapid progress achieved in renewable energy and electrification, and therefore overestimated CCS and technological CDR. The IPCC's 6th Assessment Working Group SSP1-1.9 scenario (high likelihood of a temp rise of 1–1.8°C this century), published in August 2021 (IPCC, 2021), includes 5 Gtpa of bio-energy with CCS (BECCS) and over 3 Gtpa of direct air CCS (DACCS) by 2050.
- In contrast, various recent national strategies include proportionally much lower levels of CO_2 capture and storage by 2050, instead relying on non-technological CDR solutions – particularly land use, land use change and forestry (LULUCF), which are already factored into global scenarios. These differences in outlook need to be explored and debated to inform coherent global and national strategies.

Removing emissions: BECCS and DACCS status and potential

- CDR processes combined with long-term storage are a critical component of net-zero pathways. Options include nature-based processes such as reforestation, or technology or engineered approaches such as the use of BECCS, DACCS and some other more experimental approaches.
- BECCS can, in principle, be utilised in a range of processes but the optimum application of BECCS requires more detailed investigation of costs, logistics and sustainable biomass supply chains, and will be highly country and context specific.
- In IRENA's 1.5°C Scenario, the potential for CO_2 capture per annum from processes that use biomass to which CCS could in principle be applied is c. 10 Gtpa by 2050 across multiple sectors (Table 1). The 1.5°C Scenario assumes BECCS captures and stores around 4.5 Gtpa of CO_2 in 2050 – less than half the potential. The largest opportunities are in power, heat, chemicals and biorefineries but BECCS could also be significant in cement, pulp and paper, and sugar production, and possibly also iron and steel production. But BECCS is currently not validated in these applications and there are significant complexities to be addressed in both deployments, as well as in ensuring sustainable biomass supply.
- DACCS will play a role but is only in the early stages of development, with two current commercial plants capturing only a negligible amount of CO_2. Further development and validation are needed before its potential can be properly evaluated.
- The use of CDR technologies will have a significant impact on renewable energy supply. 4.5 Gtpa of BECCS requires around 40–50 exajoules (EJ) of biomass – representing around a third of total biomass supply in the energy system by 2050. Capturing similar levels of CO_2 using current DACCS technologies would require a further c. 10% increase in the total global electricity supply by 2050 in IRENA's 1.5°C Scenario (IRENA, 2021a).

1 Global studies already assume net-zero emissions from natural CDR approaches such as LULUCF.

CCS, CCU and BECCS costs

- Carbon capture, transport and storage costs are uncertain and vary by application, with estimated costs of USD 22–225/tCO_2. With CCS applied to the production of ammonia and methanol at the lower end, hydrogen and cement production the middle, and iron and steel, and then ethylene, at the higher end. BECCS costs are estimated at USD 69–105/tCO_2, with power plants co-firing biomass at the lower end, ethanol from sugar cane in the middle and cement plants towards the higher end.

Challenges and actions

- Delivering a significantly increased uptake of CO_2 capture faces the interlinked challenges of: limited current deployment; limited infrastructure for CO_2 transport and storage; limited operational experience; uncertainties concerning optimal use; limited existing policies and regulations; high and uncertain costs; less than 100% capture rates; lack of commercial incentives; lack of business cases; and some societal reservations. All these factors need to be urgently addressed.
- For the technologies to be scaled-up, actions on multiple fronts are needed, including: many more demonstration and first-of-a-kind projects in multiple regions of the world with experience shared widely; increased and sustained research, development and demonstration (RD&D) funding; robust life-cycle analysis; an enabling regulatory framework, government mandates and standards; technology-promoting institutions and organisations; financial incentives such as grants and tax-credit mechanisms; the active promotion of CCS technologies to the public; globally distributed CCS hubs, clusters and transportation networks; and, in case of BECCS, sufficient sustainably sourced biomass feedstock.
- Ambitious action this decade is critical to keeping the 2050 goals in sight. The UN's Race-to-Zero Emissions Breakthroughs initiative calls for public commitments to be made to capture 100 Mtpa by 2030 using engineered solutions for carbon removal (e.g. BECCS and DACCS) with at least 75 Mtpa CO_2 permanently stored in materials or geological formations (excluding EOR), and for public and private actors to establish over 50 new CCS/CCU networks reaching final investment decisions (FID) by 2026, totalling 400 Mtpa in new capacity including in one or more of the heavy industries (Climate champions, 2021).
- Achieving these goals will require diverse coalitions of actors developing and implementing shared plans. International co-operation will be an essential enabler of rapid progress and vital in ensuring all nations access or develop the knowledge and capacity to allow the rapid global adoption of these emerging technologies.

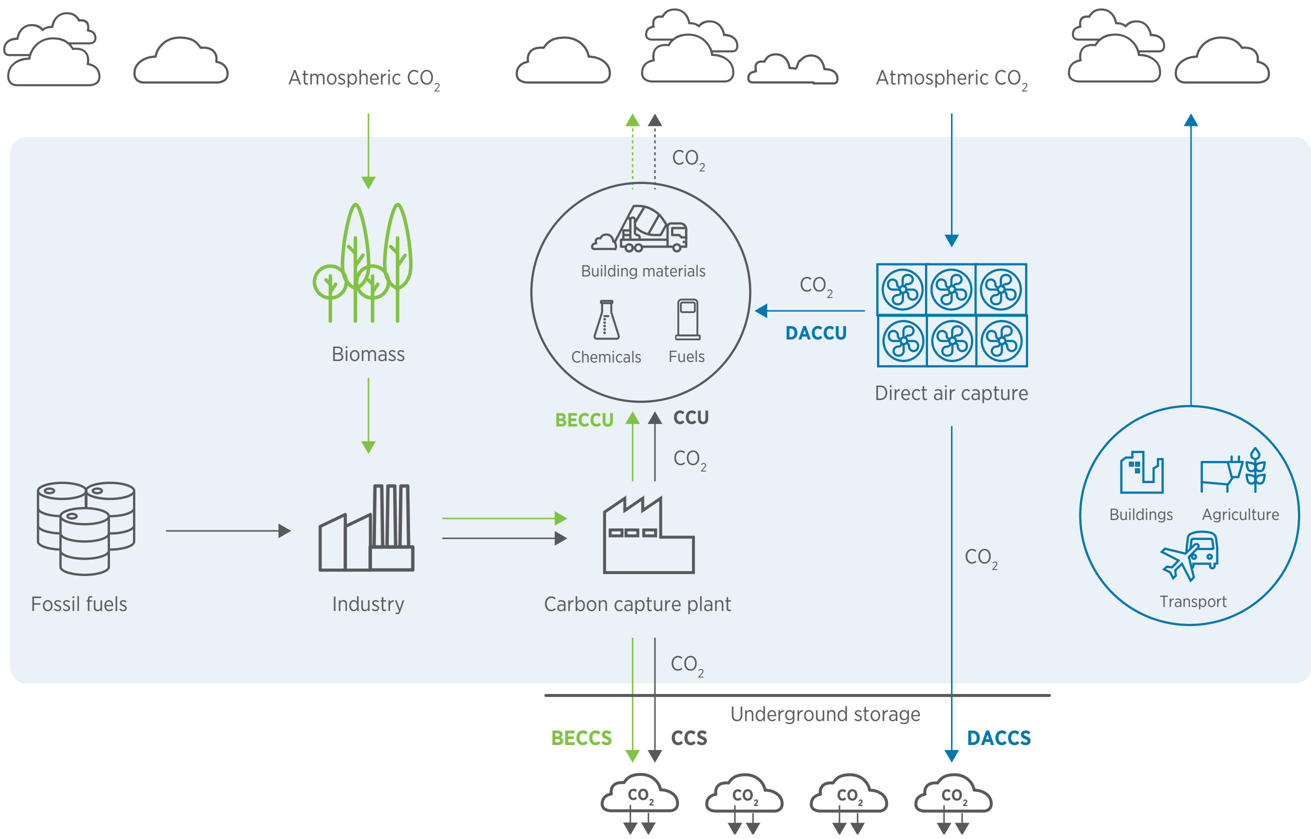
1

THE ROLE OF CARBON CAPTURE

CO_2 capture solutions are a component of the global energy transition.

- In the 2015 Paris Climate Change Agreement, countries committed to striving to limit global temperature rises to well below 2°C and to reach net-zero emissions by the second half of this century. In the years since, a growing range of countries and organisations around the world have committed themselves to trying to limit temperature rises to no more than 1.5°C, and to reaching net-zero emissions by mid-century.
- In support of its member countries, IRENA works with governments and other stakeholders to analyse and explore the strategies needed to achieve that goal. In March 2021, IRENA published a preview of its annual roadmap for the global energy transition and in June 2021 the full report was published. The 2021 edition – the *World Energy Transition Outlook* – (IRENA, 2021a) for the first time focused on a 1.5°C compatible scenario that sees emissions declining rapidly and reaching net-zero by 2050. That analysis shows that a credible but narrow pathway exists, but it also makes clear the scale of the challenges faced in delivering that pathway and the need for massively accelerated pace in many areas. To deliver on that goal will require major efforts on all fronts and the use of all decarbonisation tools in the toolbox.

FIGURE 2: Carbon cycle

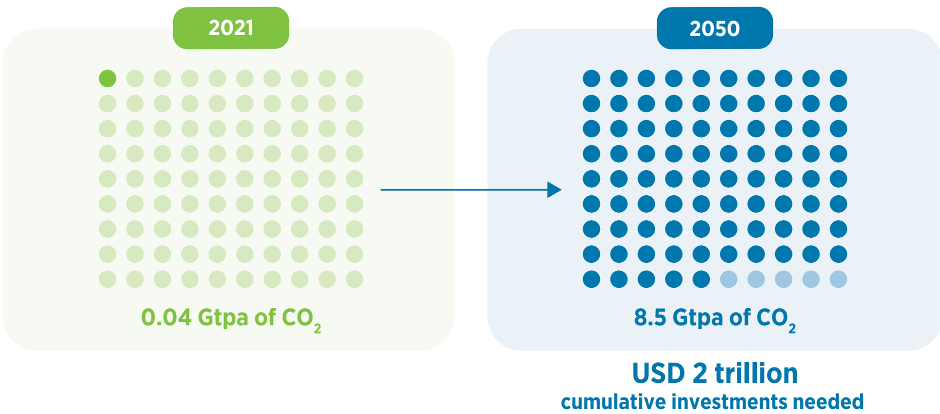


- IRENA's analysis shows that the use of renewables alongside efficiency improvements can deliver most of what is needed, providing 80% of the required CO_2 emissions reductions. Renewable sources, including renewable power generation sources and the direct use of renewable heat and biomass, would contribute to 25% of CO_2 emissions reductions, an additional 25% of CO_2 reductions would come from the reduced demand compared to the baseline scenario, efficiency improvements and circular economy. The electrification of transport and heat applications would account for 20% of CO_2 emissions reductions, while the use of hydrogen and synthetic fuels and feedstocks would enable 10% of CO_2 emissions reductions (IRENA, 2021a).
- However, the scale of the challenge, the relatively limited time available, the legacy of systems built around fossil fuel use, and the complexities of some industrial processes mean that even a very aggressive ramping up of renewables will not be sufficient to address all emissions. Some fossil fuel use will remain in 2050 and some industrial processes will produce CO_2 emissions irrespective of the energy source.
- There is a targeted role, therefore, for a combination of carbon capture and storage (CCS) processes that reduce emissions released into the atmosphere, for carbon capture and utilisation (CCU) processes that might reduce emissions, and for carbon dioxide removal (CDR) processes which, combined with long-term storage, can remove CO_2 from the atmosphere, resulting in negative emissions.

Progress in capturing carbon is well off the pace needed, whilst other low-carbon technologies are accelerating.

- The use of renewables, coupled with reductions in energy intensity, will be the principal pillars of a net-zero pathway, accounting for 80% of emission reductions in a 1.5°C scenario. To-date, CO_2 capture and storage has made no meaningful contribution to mitigating GHG emissions; however, renewables and energy efficiency will need to be supplemented in some contexts by CO_2 capture and storage. IRENA's 1.5°C Scenario assesses that CO_2 capture rates should reach c. 6.1 Gtpa of CO_2 by 2040 and 8.5 Gtpa by 2050.
- The scale of that level of capture by technologies is comparable to the amounts currently captured by the whole of the world's forests (which are estimated to currently absorb a net 7.6 Gtpa of CO_2, although there is a high degree of uncertainty with this estimate) and the volume of CO_2 stored will be two and half times the volume of oil currently extracted per annum globally (Harris et al., 2021; MacDowell et al., 2017).
- Progress in scaling up the use of CO_2 capture processes in the past two decades has been characterised by over promising and under delivering. CO_2 capture capacities have doubled from a decade ago but still only reached 0.04 Gtpa of CO_2 being captured globally by only 24 plants, which is less than 0.1% of global energy- and process-related emissions. Annex A section 1.2 expands on these points.
- The lack of progress is in large part due to the high costs and lack of regulatory certainty, long-term signals and economic incentives, rather than technology challenges. However, the potential of some technologies and processes is now better understood.
- Crucially, the growing global consensus on the importance of net-zero emissions by mid-century is changing the business case for CO_2 capture and storage and greatly increases the urgency of its deployment.
- There are some signs of momentum building and the pace is increasing, but it still falls far short of what is needed. Globally, around 30 projects are in development, which if deployed would result in a combined 0.1 Gtpa of CO_2 captured; however, a 1.5°C consistent pathway could require between 1 Gtpa and 2 Gtpa of CO_2 capture by 2030. Delivering c. 2 Gtpa of capture and storage by 2030 would require cumulative investments of the order of USD 0.4 trillion by 2030 (EC, 2021; Global CCS Institute, 2020a; MIT, 2016). To put this amount in content, USD 0.4 trillion represents approximately 2% of the annual gross domestic product (GDP) of the United States and 2.5% of annual GDP of the European Union. Annex A section 1.2 and Annex B expand on the CO_2 capture approaches and projects across industries.
- Keeping a 1.5°C pathway within reach will require as rapid and as massive a scale-up of deployment this decade as possible. By 2025, the increase will be mostly seen in hydrogen plants, but by 2030 significant progress is also needed in the cement, chemicals and power sectors.

FIGURE 3: The scale of global carbon capture installed capacity required



CCS, CCU and CDR have different impacts of emissions and distinct roles to play.

- Distinctions need to be made between the roles and system values of CCS, CCU and CDR. The total impact on atmospheric CO_2 concentration in the next few decades is the key criterion, and the specifics of different technologies and their application will have varying impacts.
- The terms CCS, CCU and CDR are often conflated with CCUS or CCU/S, which are often used as shorthand for CCS and CCU, and sometimes for all three. But in the context of the need for deep decarbonisation – and in particular the net-zero goal – it is important to distinguish between them. They share some common elements but their roles and impacts on net emissions of CO_2 vary.
- **Carbon Capture and Storage (CCS)** refers to processes that directly capture CO_2 emissions from "point sources" – i.e. from fossil-fuel use or industrial processes with the CO_2 subsequently stored in ways that lock it away for long periods.[2] If effectively implemented, the process reduces most of the CO_2 emissions being released into the atmosphere, although usually not all.
- **Carbon Capture and Utilisation (CCU)** refers to processes that directly capture CO_2 emissions from "point sources" – i.e. from fossil-fuel use or industrial processes – but then utilise that CO_2 in secondary processes such as producing synthetic fuels, chemicals and materials.[3] As with CCS, if effectively implemented, CCU reduces some CO_2 emissions being immediately released into the atmosphere but, depending on the life-cycle of the products produced, some or all of the utilised CO_2 may be subsequently released into the atmosphere. The impact of CCU on emissions is complex therefore and must be carefully managed.
- **Carbon Dioxide Removal (CDR)[4]** refers to processes that actually "remove" CO_2 from the atmosphere rather than simply reduce what is added. If combined with long-term storage, these can result in negative emissions. These technologies and practices are sometimes therefore called negative emissions technologies (NETs) and include natural approaches such as afforestation or reforestation and technological or engineered approaches such as the use of bioenergy coupled with CCS (BECCS) or direct air capture and storage (DACCS) (Box 1). Annex B, sections 2.2 and 2.3, provide more details on the capture of CO_2 through BECCS and DACCS, while Annex F section 6.1 expands on BECCS and Annex F section 6.2 expands on DACCS.

BOX 1: BECCS and DACCS

CDR Technologies Remove CO_2 from the atmosphere rather than simply reduce what is added.	
BECCS **(bioenergy with carbon capture and storage)** When growing, biomass captures CO_2 from the atmosphere. In power or industrial processes, the biomass (or fuels derived from the biomass) is combusted, releasing CO_2. In BECCS the majority of that CO_2 is captured and then stored. BECCS applies the same technology as CCS with the difference that it uses biogenic feedstock/fuels.	**DACCS** **(direct air carbon capture and storage)** Instead of capturing CO_2 from point sources such as relatively high concentration flue gas streams, the CO_2 is separated from ambient air. The low concentration of CO_2 in ambient air requires a higher surface area of solvents or sorbents in their liquid or solid form in contact with the input air stream, as well as a large amount of energy.

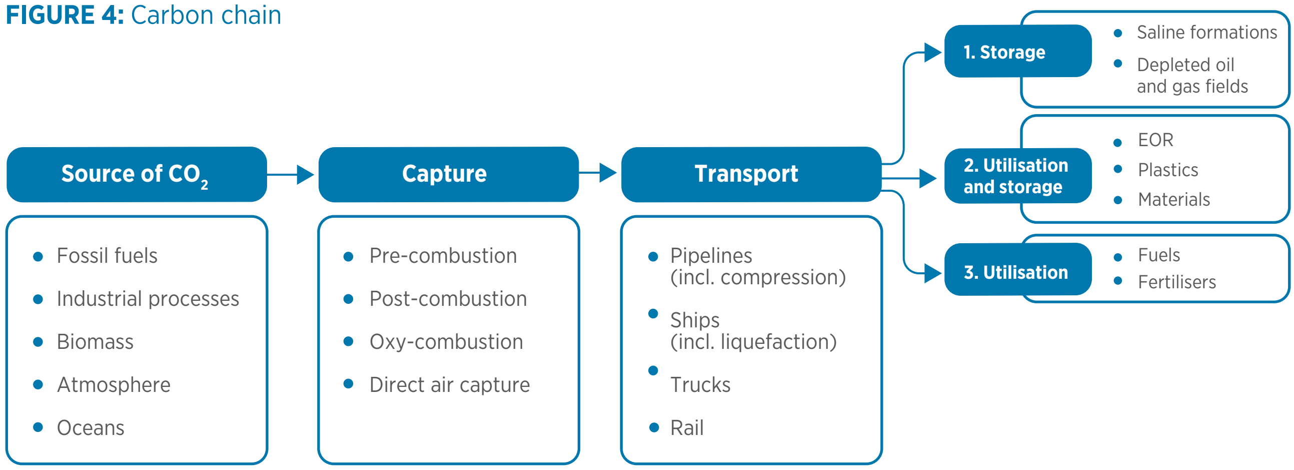
2 There is no agreed definition of how long but as a guide the storage needs to be sufficiently long term such that at as a minimum any later release does not impact atmospheric CO_2 levels this century.

3 A common current use of captured CO_2 is in enhanced oil recovery, where the CO_2 is pumped into oil fields. In principle the CO_2 remains stored underground, and therefore this 'use' could be characterised as CCS.

4 CDR techniques – particularly BECCS and DACCS – are distinct from geoengineering techniques such as solar radiation management (SRM). Geoengineering refers to a broad set of methods and technologies that aim to deliberately alter the climate system in order to alleviate the impacts of climate change (IPCC, 2011).

- CCS, CCU and CDR share some major components, as shown in Figure 4.

FIGURE 4: Carbon chain



BOX 2:

Emissions removal vs. reduction

When addressing CO_2 emissions, there is often conflation between the concepts of **CO_2 emissions removal** and **CO_2 emissions reduction**. Both concepts involve capturing carbon dioxide, but their categorisation depends on the source of CO_2, which is critical for decision making in the context of very constrained carbon budgets.

CO_2 emissions reduction refers to situations in which the CO_2 is a waste gas from burning fossil fuel, and is captured and then stored for the long-term. This CO_2 would have otherwise been destined for the atmosphere, adding to net CO_2 levels. **The source of CO_2 is fossil fuels.**[5] Emissions reduction technologies are relevant to fossil-fuel use in industrial processes, for hydrogen production and for power generation. CCS and CCU processes are, in most contexts, examples of carbon emissions reduction. **CO_2 emissions reduction processes can reduce new emissions but do not lead to a net reduction in CO_2 in the atmosphere or oceans.**

CO_2 emissions removal refers to the removal of CO_2 from the atmosphere that is then stored long term – i.e. it leads to a net reduction of CO_2 in the natural environment. **The source of CO_2 is the atmosphere.** These **carbon dioxide removal (CDR)** measures involve extracting CO_2 directly from the atmosphere or oceans, or indirectly via the sustainable growth and use of biomass. In the energy system context, the principal ways of doing this are the use of biomass (bioenergy) with CCS (BECCS), and direct air capture with storage (DACCS), but other potential CDR methods include reforestation, afforestation, ocean fertilisation, biochar and enhanced weathering. **CO_2 removal processes can lead to a net reduction of CO_2 in the atmosphere;** but context matters too, if the biomass is not sustainably sourced, the direct air capture is powered by fossil fuels; and if captured CO_2 is used to produce products that eventually release their CO_2 (e.g. synthetic fuels), it may not result in a net reduction in emissions

5 In the case of cement production, the source of CO_2 is limestone.

The potential role of CO_2 capture, utilisation and storage is contentious and at times confusing; a more nuanced and shared understanding must be developed.

- CCS, CCU and CDR are contentious topics, with opinions on their role often starkly divided.
- For CCS and CCU, the debate pivots around four points: the continued use of fossil fuels; investments and future costs of CCS relative to alternatives; perception of CO_2 transport and storage safety; and overall effectiveness in reducing CO_2 emissions.
- Many of the same arguments for CCS apply to CCU, although utilisation likely has a higher societal acceptability since it reduces safety concerns about CO_2 onshore transport and storage. Its role will be mostly in the short term, but in the long term, CCU is compatible with a net-zero emissions future only if the CO_2 source is sustainable (biogenic or air) or the utilisation results in the long-term storage of CO_2 (e.g. in building materials). By generating some profit from the sale of the CO_2 captured, in the short term CCU may trigger a scale-up in the deployment of CO_2 capture plants. Annex A, sections 1.5 and 1.6 provide more details on the role of CCS, CCU and CDR.
- The role of CDR is slightly less contentious, but concerns remain about the moral hazard of the potential for the later use of CDR being used as an excuse for less urgency in emissions reductions now. CDR technologies, particularly BECCS, have been assigned a complementary role by the IPCC's 6th Assessment Working Group I report published in August 2021 (IPCC, 2021), given the rapid pace needed for a 1.5°C pathway and the critical importance of emissions reductions. Annex F section 6.1 expands on BECCS, while section 6.2 expands on DACCS.
- The CO_2 produced from biomass can only be considered neutral to the atmosphere if the source of biomass is continually renewed as the biomass is harvested, and if its use does not cause other negative land-use changes. The time scale for regrowth of biomass also matters for a 1.5°C scenario – utilising biomass that takes decades to be replaced may not be consistent with the 1.5°C goal. Taking the use of BECCS in power as an example, a 660 megawatt (MW) unit (similar in size to one of the former coal units now converted to biomass at the Drax plant in the United Kingdom) requires around 2.3 million tonnes of biomass (mostly wood pellets produced from forest residues) per annum (Drax, 2020). That is equivalent to 370 000 hectares of forest, which represents approximately 12% of the UK forest area.
- DACCS is still in the development phase and to scale it up will be challenging, particularly in terms of energy, water, material and land requirements, mostly due to low CO_2 concentration in the ambient air. To put these requirements into perspective, to capture 1 Gt of CO_2 using solar-powered DAC requires circa 2 000 terawatt hours (TWh) of electricity per year, which represents almost 10% of current global electricity consumption. Annex F section 6.2 expands on various DACCS approaches and existing projects.

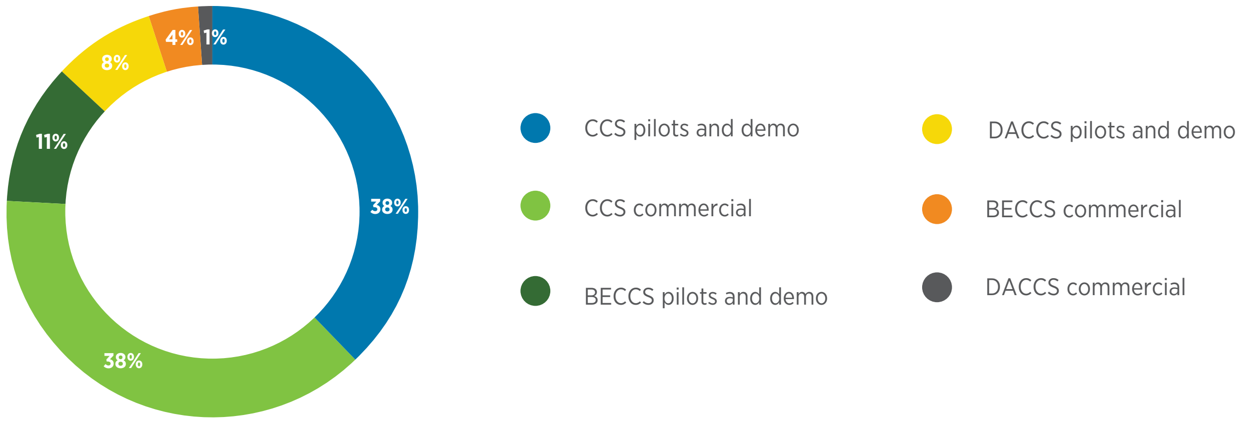
2

THE CURRENT STATUS OF CARBON CAPTURE, TRANSPORTATION, UTILISATION AND STORAGE

- As of early 2021, 24 commercial fossil fuel-based CCS and CCU facilities were in operation globally with an installed capacity to capture around 0.04 Gtpa of energy- and process-related CO_2 emissions (EC, 2021; Global CCS Institute, 2020a; MIT, 2016).
- Of these CCS and CCU facilities, 11 are natural gas processing plants (where CO_2 needs to be removed anyway to produce natural gas that meets specific standards) and one is a coal-fired power plant. Chemical plants (mostly for ethanol production), hydrogen production in refineries, and iron and steel plants account for the remainder. Three plants were operational but are now closed or suspended. An additional 30 plants are at various stages of development. A further 16 small scale pilot and demonstration plants are operating, 19 are at various stages of development, and 24 have been completed and closed (EC, 2021; Global CCS Institute, 2020a; MIT, 2016).
- If all 30 commercial plants under development are completed, the capture capacity would rise to approximately 0.1 Gtpa. Annex A section 1.2 and Annex B sections 2.1–2.3 expand on the projects across industries.

- There are currently three operational commercial facilities that use bioenergy with CCS (BECCS) and seven commercial plants are in development. The current capture capacity of operational commercial BECCS plants is very small at 1.13 Mtpa, which would rise to 9.7 Mtpa if all plants under development reach operation. A further nine smaller scale BECCS pilot and demonstration plants are operational – six completed and four in different stages of development.
- There are currently two facilities that use DACCS, with one in development, plus 15 pilot and demonstration plants in operation or development; however, collectively their capture capacities are quite small. Annex F 6.1 provides more details on BECCS, while section 6.2 expands on DACCS.

FIGURE 5: Share of commercial, pilot and demonstration projects for CCS, DACCS and BECCS



Source: Based on EC (2021); Global CCS Institute, (2020a); MIT (2016).

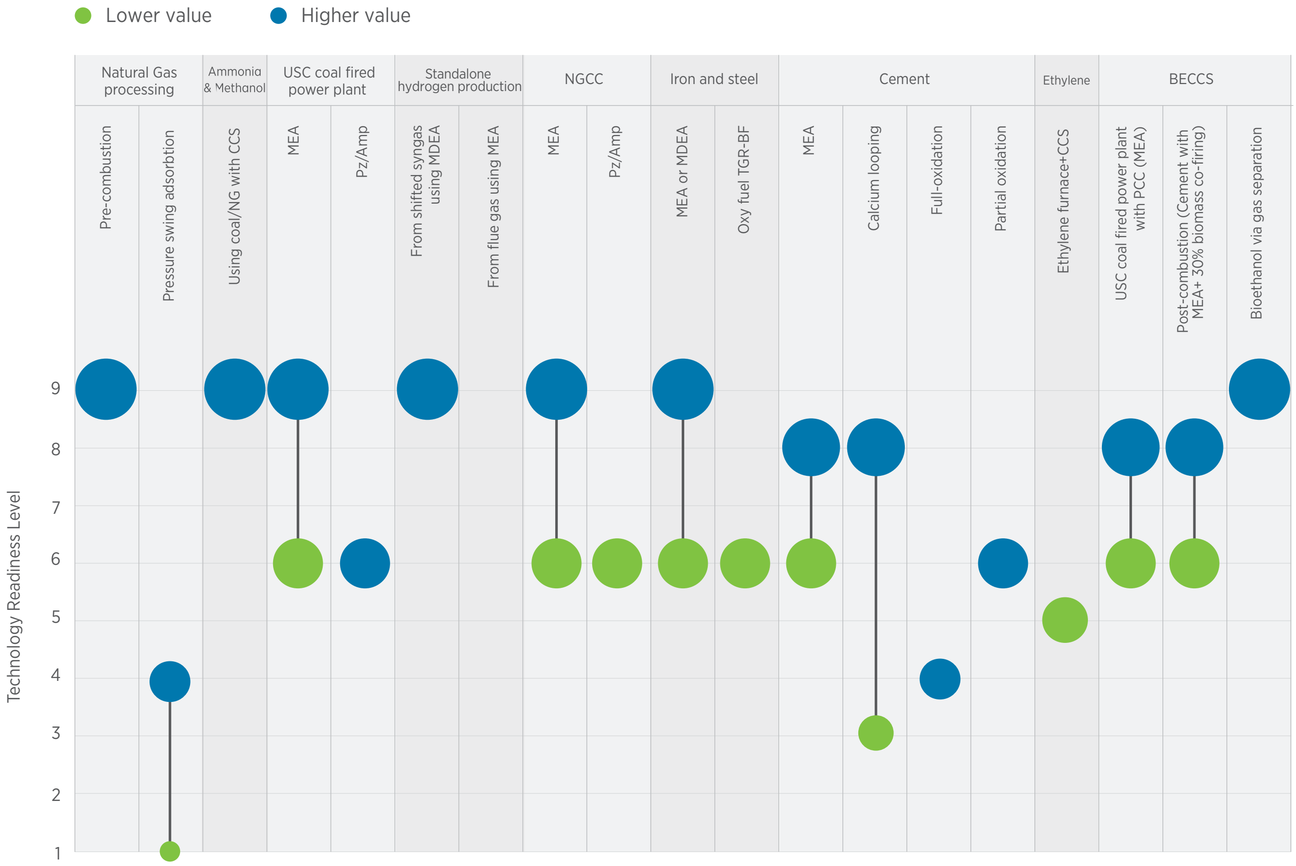
- Capture technologies are at different technology readiness levels (TRLs[6]) with some as low as TRL 1, but many at or reaching TRL 9 and so could be sufficiently proven to be used commercially by 2025. TRL is discussed in more detail in Annex A, section 1.2

Costs are uncertain and vary by application.

- The costs of CCS, CCU and CDR will be a crucial factor in decisions on their future roles; however, cost estimates vary widely, with future projections having a high degree of uncertainty.
- CCS is capital intensive and, in some cases, has significant operating costs. In general, capture costs dominate but in some cases CO_2 transportation costs can be significant. Actual costs are site specific and differ significantly depending on the technology used. Capture costs are mainly dependent on CO_2 concentration and pressure, and transport cost on volume and distance. Annex B sections 2.1 and 2.3–2.5 expand on various CO_2 capture technologies and costs associated with the power and industry sectors, and provide an overview of projects.
- While the costs of capture in CCU are fairly well understood, the costs of converting CO_2 into products such as fuel, fertilisers, building materials, etc. are less clear and require further research and analysis. The costs of CDR, and particularly BECCS, depend on biomass feedstock, while the costs of DACCS as a novel technology are currently very high with an uncertain cost reduction trajectory.

6 Technology readiness level (TRL) is a widely used measure of the maturity of a technology. TRL values range from 1 to 9, with TRL 1 being the lowest – referring to the beginning of the scientific research – and TRL 9 the highest, referring to a proven technology that is commercialised. More information can be found in Annex A.

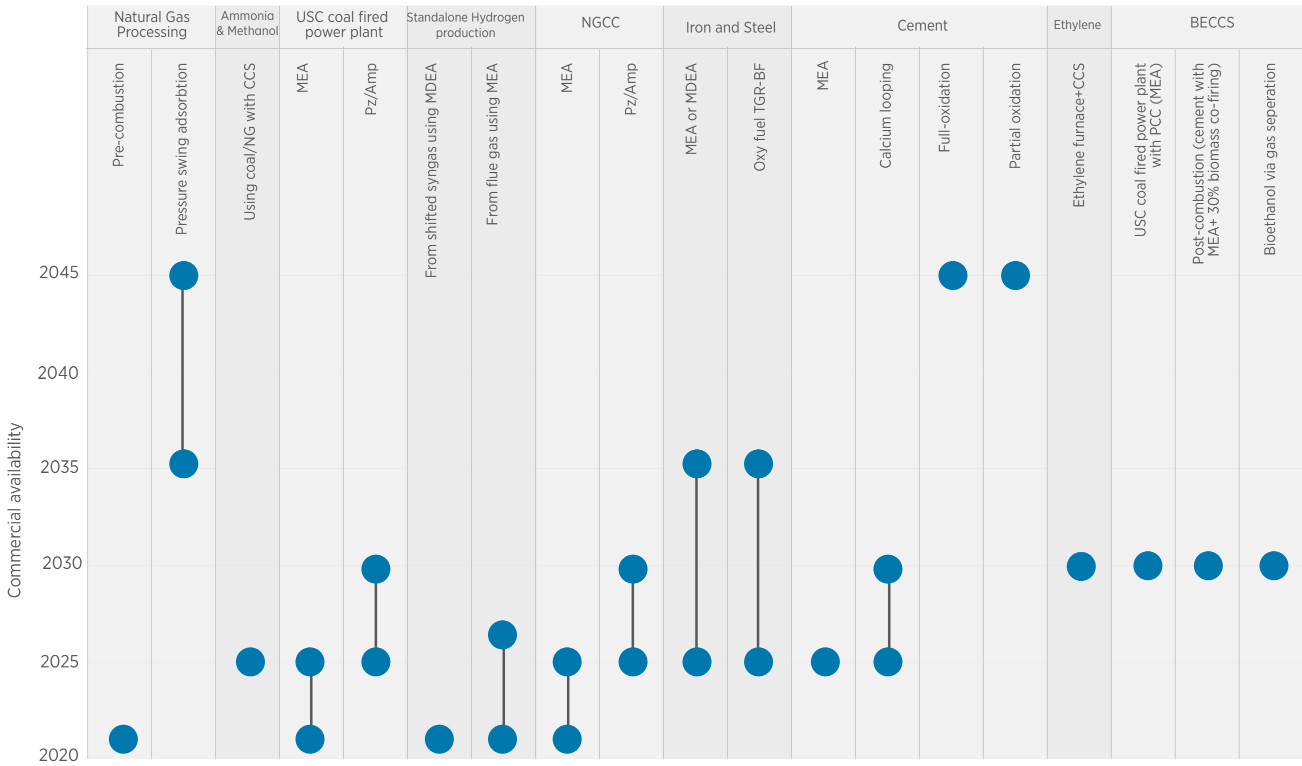
FIGURE 6: Technology readiness levels of CO_2 capture technologies



Source: Based on EC (2021); Global CCS Institute (2020a); MIT (2016).

- Many cost estimates focus only on capture costs and either do not include costs for compression/liquefaction, transportation and storage (including assessment and monitoring costs) or treat transport and storage as lump sums.
- Cost estimates tend to focus on large-scale CCS facilities with large CO_2 volumes (such as gas plants) that can justify dedicated transport and storage infrastructure, rather than smaller industrial plants that emit lower CO_2 volumes per year (such as cement plants) and will therefore have to rely on clusters, hubs and transportation networks to benefit from economies of scale. The same applies to CDR facilities. The calculated costs in feasibility studies also tend to be much lower than the costs of actual projects that have been implemented.
- When discussing and comparing costs, therefore, the project specifics and the full end-to-end project costs need to be considered.
- As CCS applied to fossil fuel processes results in additional energy use, it can in turn lead to additional CO_2 emissions and the difference can range from 10 to 25%. To account for that, *cost per tonne of CO_2 avoided* (and not cost per tonne of CO_2 captured) is the best measure to compare CCS with renewable options. Annexes A section 1.8, B sections 2.1 and 2.3–2.5, C section 3.2, D section 4.2, and F discuss in more detail, including aspects of costs in capture, transport, storage and utilisation.

FIGURE 7: Commercial availability of CO_2 capture technologies



Source: Based on Bui et al. (2018); EC (2021); Global CCS Institute (2020a); Hills, Sceats and Fennell (2019); IAEGHG (2019a); Lean et al. (2019); MIT (2016).

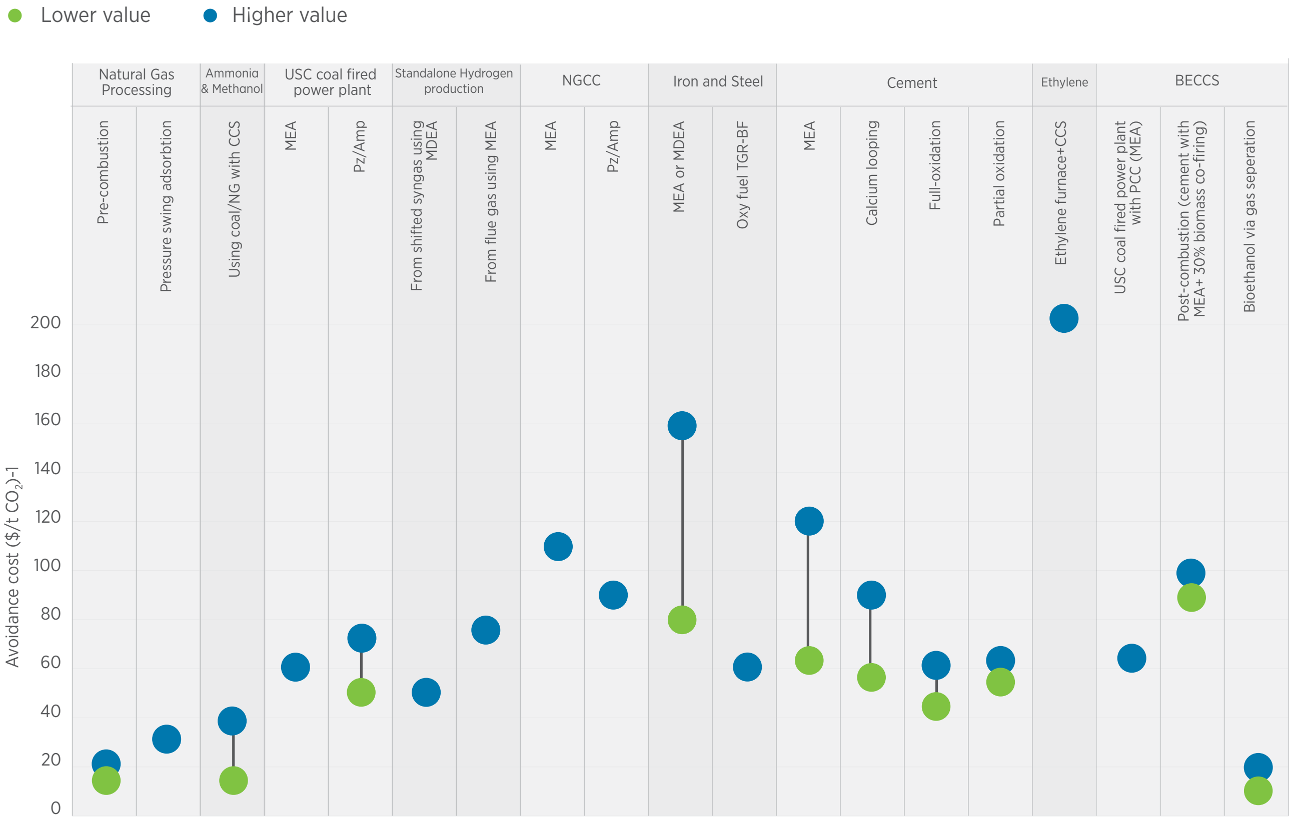
Costs for CO_2 capture vary significantly based on the sector and the technology.

- Figure 8 summarises the ranges of avoided costs of CO_2 for different potential capture technologies and in various applications, as reported by a variety of publications. The figure illustrates a high degree of uncertainty, exacerbated by the limited availability of data. With those limitations in mind, it is notable that the lowest ranges are for natural gas processing with pre-combustion, which are in the range of USD 20–25/tCO_2, while the highest costs are for the production of ethylene with CO_2 capture at over USD 200/tCO_2 (Bui et al., 2018; Hills, Sceats and Fennell, 2019, 2016, 2019; IEAGHG, 2013a, 2013b, 2017, 2019b; Khorshidi et al., 2016; Lena et al., 2019; Mandova et al., 2019; Szczeniak, Bauer and Kober, 2020; Toktarova et al., 2020; Sanmugasekar and Arvind (2019); Volsund et al., 2018).

Transportation options are proven but scale is currently limited, while cost estimates are uncertain and very context dependent.

- Transporting relatively small quantities of CO_2 is an established process and there are a few larger projects, mostly located in the US, which involve the pipeline transportation of CO_2 for enhanced oil recovery (CO_2-EOR) or EU regional transport by ships.
- With experience of transporting other more volatile gasses, the safe transportation of CO_2 is not likely to be barrier to CCS uptake, although public acceptance may remain a concern, particularly for onshore transportation options.

FIGURE 8: Avoidance costs of CO_2 capture for selected capture technologies as reported by a variety of scientific publications



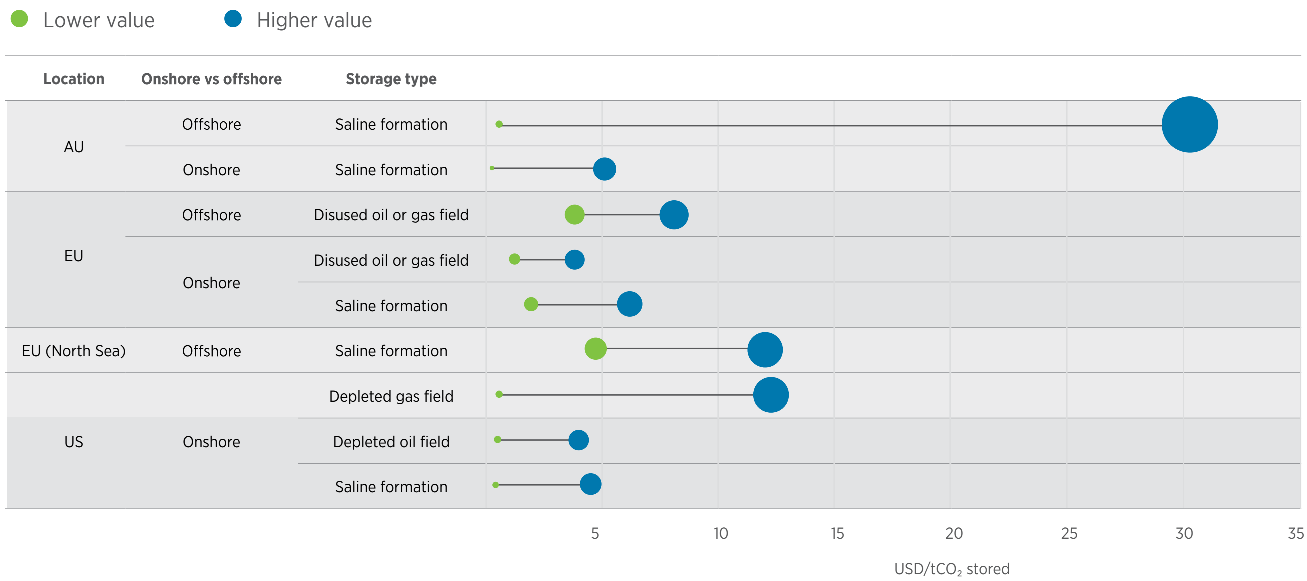
Source: Based on Bui et al. (2018); Hills et al. (2016); IEAGHG (2013a, 2013b, 2017, 2019a); Khorshidi et al. (2016); Lena et al. (2019); Mandova et al. (2019); Szczeniak, Bauer and Kober (2020); Toktarova et al. (2020); Sanmugasekar and Arvind (2019); Volsund et al. (2018).

- Costs of CO_2 transport can represent a significant share of total CCS costs and are influenced by the mode of transportation (onshore and offshore pipelines, ships, trucks and rail) and other factors such as the need for compression or liquefaction, or the distance of transport.
- There is a lack of detailed data on costs. Transport and storage costs are often modelled in the integrated assessment models as lump sums at USD 10/tCO_2 and disregard the flowrate, distance to storage and utilisation sites, transport mode and storage type, as well as the variability in geographical, geological and institutional settings. The models also focus mostly on large-scale plants with high volumes of CO_2. There are a few more detailed studies that focus on a handful of countries with established infrastructures.
- Based on current estimates, for pipelines the capital expenditure (CAPEX) is the major component amounting up to 90% of total transport costs. For transporting CO_2 by ship, the situation reverses and the major component is operating costs (OPEX) for liquefaction, fuels, loading/unloading and temporary storage.
- Based on current estimated costs for capacities of 2.5 to 20 Mtpa CO_2 for distances between 180 km and 500 km, onshore pipeline has the lowest costs at USD 1.7–6.1/tCO_2, followed by offshore pipelines at USD 3.5-32.4/tCO_2. Transport via offshore pipelines up to 1 500 km entails costs of up to USD 58.4/tCO_2. Shipping ranges from USD 12.5-22.4/tCO_2 for distances between 180 km to 1 500 km (Freitas, 2015; Gao et al., 2011; ZEP, 2011a). Annex C, section 3.2 expands on the costs involved in transport.

Geological storage of CO_2 has been carried out for many years without major issues, but the scale is small, with regional mismatches and true costs uncertain.

- Permanent geological storage options include saline formations and depleted oil and gas fields. Other storage options relate to enhanced hydrocarbons – particularly enhanced oil recovery (EOR). Geological storage in saline formations and in EOR has been carried out at Mtpa scale in past decades, but there is not yet experience in storing CO_2 at Gtpa scale, as the CO_2 captured has not yet reached Gtpa scale. Annex C details the types of CO_2 storage and their associated costs.
- The largest experience in storing CO_2 is in EOR, which has a very low risk of CO_2 leakage. For CO_2 pumped underground into geological formations, researchers expect less than 0.0008% of stored CO_2 to be leaked over 10 000 years (Alcalde et al., 2018). While the risks of leakage are small, public perceptions towards this approach may still become an issue. Monitoring and verification processes will be important, and must be a mandated and –ideally – a regulated part of any storage project.
- There is more than 12 000 Gt of potential, albeit mostly unverified, of CO_2 storage resources in saline formations globally, out of which 400 Gt of storage is currently well documented; but there are only a small number of large-scale commercial projects (OGCI, 2020). There are currently six projects storing almost 0.009 Gtpa of CO_2 in the United States, Canada, Algeria and Norway (EC, 2021; Global CCS Institute, 2020a; MIT, 2016). Fifteen sites at various stages of development will be able to store an additional 0.025 Gtpa of CO_2, broadening geographical coverage to include Germany, the Netherlands, the Republic of Korea, Sweden and the United Kingdom.
- Enhanced oil recovery is a use of CO_2 that can also constitute long term storage. It is now a well-established technology, with 20 projects in operation storing 0.031 Gtpa of CO_2. 70% of EOR storage sites are located in the United States, Canada, China and the United Arab Emirates. An additional nine enhanced oil recovery sites, based in the United States, China, the United Arab Emirates and India, are at various stages of development and will be able to store over 0.014 Gtpa of CO_2 (EC, 2021; Global CCS Institute, 2020a; MIT, 2016).
- Other related techniques that are still in their infancy include: depleted oil and gas fields, enhanced gas recovery, enhanced coal bed methane and enhanced geothermal systems.
- Unlike EOR and saline formations, there are significant uncertainties concerning costs, in part this is due to limited operational experience. With many projects in their pilot or demonstration stages, and others only laboratory simulations, reliable data on actual costs is scarce.
- Costs will also be highly site-specific and influenced by many factors such as location (country, onshore or offshore), type of storage, storage capacity, and annual storage rate and quality. Costs estimates are currently available for onshore and offshore saline formations and depleted oil and gas fields on three continents: the United States, the European Union (EU) and Australia (Figure 9). Common outcomes from cost estimates indicate that onshore storage is cheaper than offshore storage, and that depleted oil and gas fields are cheaper than saline formations. Onshore storage, however, may face social and political resistance, and legal barriers. The widest cost ranges are for offshore saline formations.
- Depending on the continent, onshore saline formation cost estimates range from USD 0.2–6.2/tCO_2, with the cheapest storage in Australia and the most expensive in the EU. Offshore saline formation costs range from USD 0.5-30.2 /tCO_2, with a lower range in Europe. Costs estimates for depleted oil onshore fields in the US range from USD 0.5-4.0/tCO_2, and gas onshore fields in the United States range from USD 0.5-12.2/tCO_2. Cost estimates for depleted onshore oil and gas fields in the EU range from USD 1.2-3.8/tCO_2, with offshore at USD 3.8–8.1/tCO_2. These cost ranges come with many caveats; in particular, lower ranges look optimistic and it is unclear how much they include the costs of monitoring, verification or pressurisation (IPCC, 2005a; ZEP, 2011a). Annex D section 4.2 expands on the costs of CO_2 storage.

FIGURE 9: Cost estimates for onshore and offshore storage



Source: Based on IPCC (2005).

Total end-to-end process costs are uncertain but are generally high and, in many contexts, commercial incentives to invest are low.

- Cost estimates of avoided CO_2 for carbon capture, transport and storage range from USD 22-225/tCO_2 depending on the sector, capture technologies, distance from storage and storage location.
- The lowest range is for the production of ammonia and methanol (USD 22–62/tCO_2), followed by natural gas processing plants (USD 31–49/tCO_2) and production of hydrogen (USD 73–88/tCO_2). The highest range is in the iron and steel industry, with costs of USD 75–131/tCO_2, followed by the cement industry (USD 62–102/tCO_2), with the most expensive price put on the production of ethylene (USD 212–225/tCO_2)[7] (IPCC, 2005; ZEP, 2011b).
- Cost estimates for bioenergy with carbon capture, transport and storage also vary significantly depending upon the sector of application (USD 69–105/tCO_2).
- The range can be even broader when including the sourcing of biomass; for example, for power plants co-firing biomass (USD 69–85/tCO_2) and for cement plants (USD 76–105/tCO_2) (IEAGHG, 2019a; Khorshidi et al., 2016; Mandova et al., 2019; Sanmugasekar and Arvind, 2019).
- CCS proponents claim significant potential for learning effects through learning-by-doing and learning-by-innovating, and project significant cost reductions going forward. It is not possible to validate such claims but, given the limited deployment to date and many cost reduction drivers, cost reduction through learning and economies of scale is likely – however, to what extent remains highly uncertain. Annex A section 1.8 expands on these aspects.
- As CCS, CCU and CDR plants do not directly bring commercial benefit to investors and require high CAPEX and OPEX, a financial incentive is crucial to their deployment. This could be achieved by direct financial support and/or indirectly through emissions standards or carbon taxes that create the business case. Access to funding is challenging and has not always been stable. Countries therefore need to create stable, balanced but dynamic financial support to improve confidence within the private sector. Existing forms of financial support from around the world include tax credits, grants and loan guarantees.

7 These estimates include the costs of transport and storage of CO_2. Transport costs include onshore or offshore pipeline transport for distances of 180 km to 500 km. Storage include costs for both offshore and onshore geological storage.

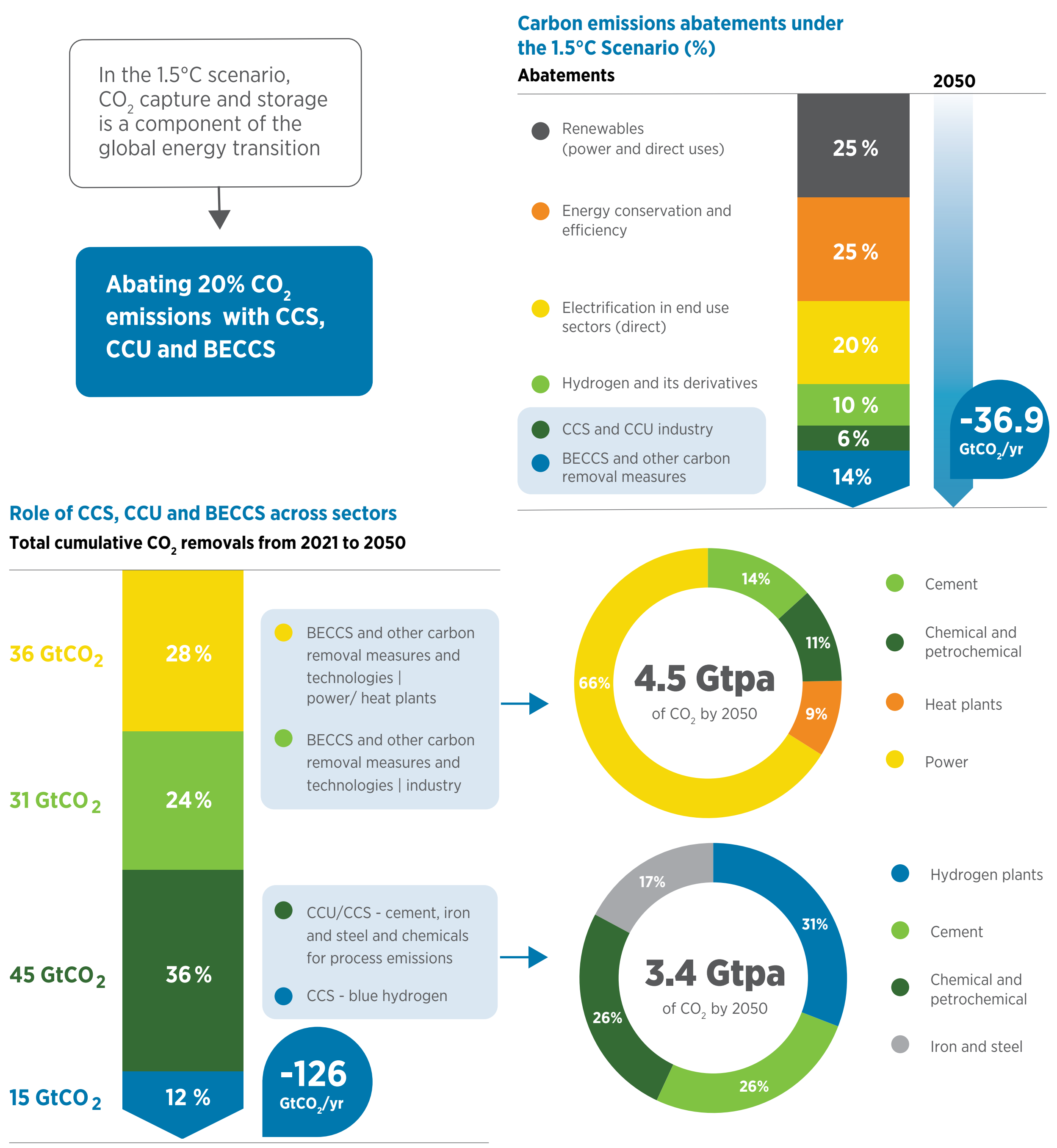
3

THE FUTURE ROLE OF CCS, CCU AND CDR

Low-cost renewables make carbon capture combined with fossil fuel use unnecessary in many sectors and contexts, but it will be needed in some applications.

- Renewables and CCS (applied to fossil fuel use and/or process emissions) are often perceived as competitors in the energy transition but in some applications they can be partners and, in a few cases, CCS is the only option.
- The respective roles of renewables versus CCS vary by country, sector and the specific contexts of each deployment. Factors of importance include: relative costs; practicality of deployment; availability of supporting transport and storage infrastructure; actual emission abatement potential; deployment time scales; skills and knowledge; social impacts; and societal attitudes.
- In most contexts in the power sector, renewables outcompete CCS on cost per tonne of CO_2 and sustainability grounds.
- IRENA's annual assessment of renewable power generation costs for 2020 (IRENA, 2021b) showed that, increasingly, newly installed renewable power capacity costs less per kWh than the cheapest unabated fossil fuel-based generation options. Electricity costs from utility-scale solar PV fell 7% year-on-year, reaching nearly

FIGURE 10: The role of CCS, CCU and BECCS across sectors

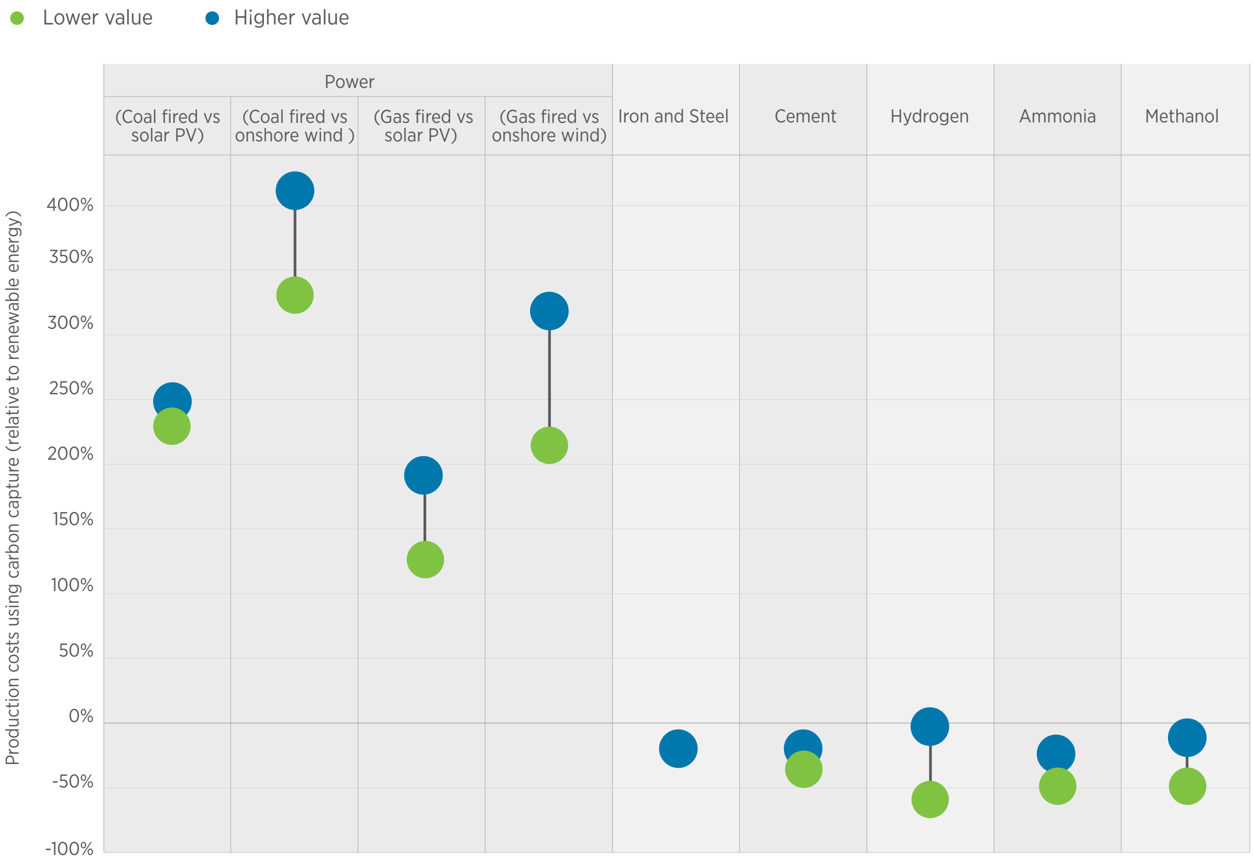


Note: BECCS = bioenergy with CCS; $GtCO_2$ = gigatonnes of carbon dioxide.

six cents (USD 0.057) per kilowatt hour (kWh) in 2020. Onshore and offshore wind both fell by about 9% and 13% year-on-year, reaching 0.039 USD/kWh and 0.084 USD/kWh, respectively, for newly commissioned projects. More than half of the renewable capacity added in 2020 achieved lower electricity costs than new coal. Levelised costs per kWh of electricity for coal-based power production with CCS are currently 44% more than the average cost of solar and 85% more than average costs of onshore wind in the markets examined.

- In the power sector, therefore, CCS per kWh use is not economically justifiable for new fossil fuel projects. The only economic case that can be made for its use is to utilise existing installed infrastructure, but even in this context new renewable installations can deliver lower-cost power than coal plants with CCS retrofits, and provide both stable and well-paid jobs. From a current cost perspective, the use of CCS is economically justifiable per tonne of CO_2 for the production of hydrogen, ammonia, methanol, cement, and iron and steel (Figure 11). Annex A section 1.8 and Annex B sections 2.3–2.5 expand on the costs of CCS versus renewables and other options.

FIGURE 11: Costs[8] of production via carbon route, as a percentage of renewable pathway



Processes to capture CO_2 do not remove all CO_2 and still result in some emissions that must be accounted for.

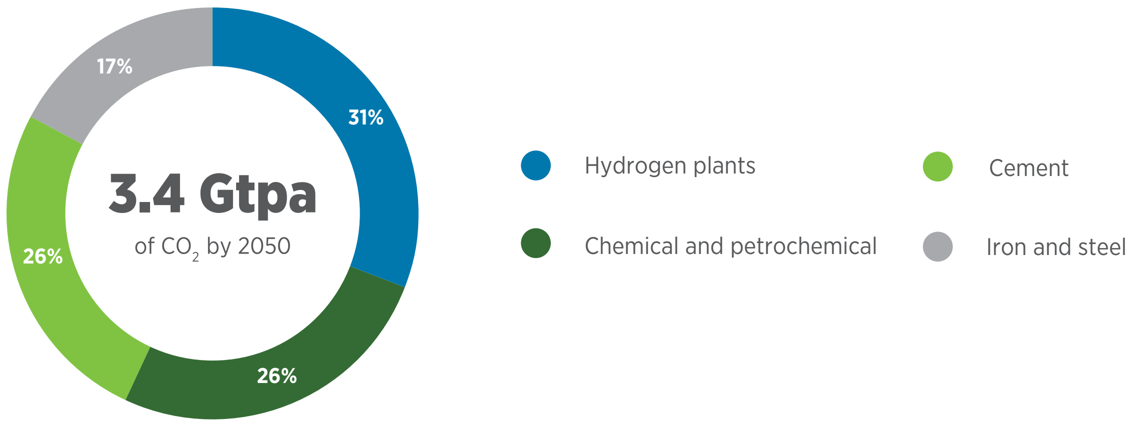
- CO_2 capture processes across the power and end-use sectors are not 100% effective. Current deployments of CCS often have capture rates of 60–80% or less. Around 90% capture rates are often referenced in discussions of CCS but are neither a technical or economic limit – in principle, higher capture rates are possible in many applications, in some case approaching 99% but such deployments are not yet demonstrated at scale and will impact costs. CCS deployments should be incentivised to push capture rates as high as possible (e.g. >95%) but some emissions will remain that must be accounted and compensated for in any system aiming for net-zero emissions.

8 The calculation of relative costs does not look at unabated costs but rather considers production costs via renewables as the base costs for different commodities. This shows how expensive or cheap the commodity produced with capture technology is, compared to that produced using the renewables route. For several sectors, this is expressed as a range denoting the variation of costs in different geographies with the same production route.

- As with any technology seeking to reduce CO_2 emissions, conducting full lifecycle assessments including both upstream and downstream emissions is important. For CO_2 capture processes, upstream emissions associated with the continued extraction and transportation of fossil fuels, or with sourcing of biomass, must be accounted for, with methane emissions and leaks being particularly significant. If fossil fuels continue to be used, steps must be taken to significantly reduce leakages, with any remaining emissions included in assessments of the value and cost of CCS. Downstream emissions – for example, from the utilisation of captured CO_2 – are also important and must be included in assessments.

Carbon capture for fossil fuel and process emissions in industry must be aggressively scaled to reach c. 3.4 Gtpa by 2050.

FIGURE 12: Share of CO_2 capture, utilisation and/or storage by sector by 2050



- In IRENA's 1.5°C Scenario, the use of CCS and CCU for fossil fuel or process emissions is limited to the most essential applications – in particular to capturing process emissions in hydrogen, cement, iron and steel and chemical production with a limited deployment for industry/waste incinerators, etc. CCS is not deployed for fossil-fuel based power production.
- In the 1.5°C Scenario, CCS and CCU for fossil fuel or process emissions from power, fuel production and industrial process rises from 0.04 Gtpa today to 2.8 Gtpa of CO_2 in 2040 and 3.4 Gtpa of CO_2 in 2050, cumulatively capturing 58 Gt globally over that period.
- These figures include 2.4 Gtpa in 2050 from CCS applied in the cement, chemical and steel sectors, and 1.1 Gtpa in 2050 captured in the production of blue hydrogen from natural gas with CCS, which accounts for c. 30% of total hydrogen supply (Figure 12).

Utilisation has a role but should be mainly limited to applications that do not lead to the later release of the CO_2.

- CO_2 utilisation is a potential way to improve the economic feasibility of carbon capture by creating a revenue stream from captured CO_2. In some contexts, it can also compensate for a lack of readily available and accessible CO_2 storage sites; utilisation may also serve to avoid social acceptance issues concerning CO_2 storage.
- There are, however, two very important caveats in this regard. Firstly, the scale of CO_2 use applications is relatively small compared to the levels of CO_2 capture required this decade. Secondly, many utilisation routes are not consistent with reaching net zero emissions, because the captured emissions are released back into the atmosphere in the short or medium term.
- There are several potential utilisation pathways. CO_2 can be used in enhanced hydrocarbon recovery (such as oil, gas or coal bed methane) and to produce fuels (methanol, hydrogen, syngas, biofuels via algae), commodities (urea, methanol) and chemicals (polymers), or through CO_2 mineralisation to produce building materials.
- Captured CO_2 is currently used to a very limited degree in some goods in the beverage industry, and in ethanol, methanol or fertiliser production, accounting for approximately 230 Mtpa of CO_2 (MacDowell et al., 2017).
- Challenges associated with utilisation include immature technologies that are also capital and energy intensive, they need to be located in vicinity of capture plants to reduce transportation costs, and have a commercial market. Demand for CO_2 will likely depend mostly on the large-scale implementation of CO_2-based fuels.
- In the short term, CCU can play a role in reducing emissions by replacing carbon intensive products with less intensive alternatives. In the long-term, CCU is only compatible with a net zero emissions future if the CO_2 source is sustainable (biogenic or air) or the use results in the long-term storage of the CO_2 (materials).
- In the 1.5°C Scenario, CCU applied to fossil fuel or process emissions has a small role in the short term as source of carbon; in the medium term, however, its role is limited to those circumstances that do not lead to a net increase in emissions to the atmosphere – mainly in the chemical sector – accounting for circa 14% of the CO_2 captured through to 2050 in the 1.5°C Scenario (IRENA, 2021a). Annex E expands on the topic of CO_2 utilisation.

Bioenergy with CCS (BECCS) is essential for the net-zero goal but needs to reach 4.5 Gtpa by 2050 and faces multiple challenges.

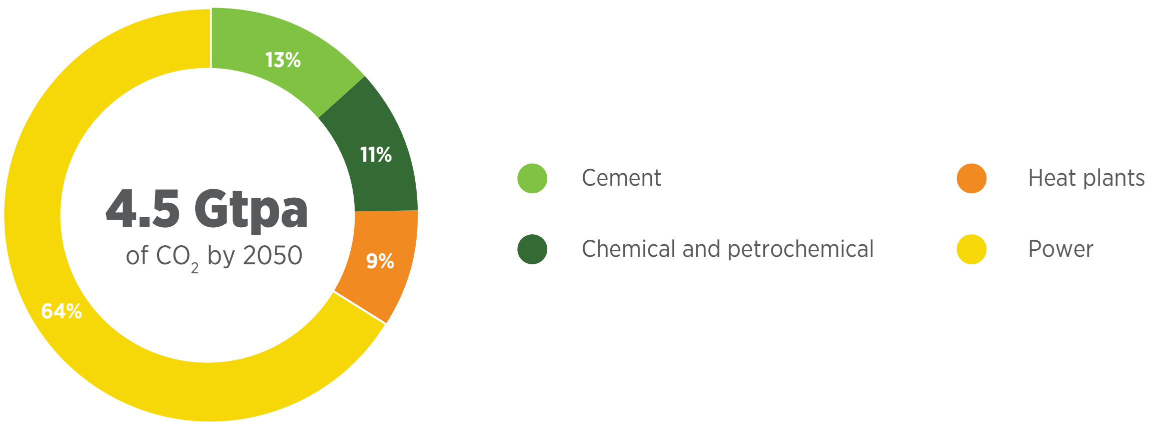
- CDR processes, combined with long-term storage, can in principle remove CO_2 from the atmosphere, resulting in negative emissions. CDR technologies are therefore a critical component of net-zero pathways.
- CDR measures and technologies can include nature-based processes such as reforestation, as well as technology or engineered approaches such as BECCS, DACCS and some other experimental approaches.
- The most developed example of CDR technology is BECCS. Biomass absorbs CO_2 from the atmosphere as it grows, and the use of CCS prevents most of that CO_2 from going back to the atmosphere during biomass final use. The overall result is that CO_2 is effectively removed from the atmosphere through biomass growth and storage elsewhere.
- Net-zero pathways rely on BECCS but it is currently unproven in most contexts and there are complexities to be addressed. The extensive use of BECCS requires both a scaling up of CCS deployment and strategies to ensure sufficient suitable and sustainable biomass feedstock supplies. IRENA's 1.5°C Scenario foresees a need for c. 40–50 EJ of biomass utilised with BECCS – around a third of total biomass used in the energy system (IRENA, 2021a).

- There are a range of potential applications of BECCS, including: power and heat generation with biomass providing some or all of the fuel (e.g. wood pellets, sugarcane bagasse or municipal solid waste); cement kilns with biomass providing the fuel; blast furnaces for iron production, where charcoal can be used as a fuel and reducing agent; chemical plants where the chemical feedstock is biomass (e.g. bio-methanol or in bioethanol production); and biogas upgrading where the CO_2 fraction of biogas is separated for the production of biomethane.
- Depending on the plant design, biomass can be the only fuel, or it can be co-fired with coal or natural gas. In the past decade, a small number of coal power plants have been converted into 100% biomass power plants or are in the process of doing so. However, the number of such conversions to date is small and only one fully converted power plant has a clear publicly announced plan to add CCS; as yet, no co-firing coal or natural gas power plants have announced plans to add CCS (Drax, 2021; Voegele, 2021). Annex B sections 2.3–2.4 and Annex F section 6.1 expand on the role of BECCS.
- The IPCC's 6th Assessment Working Group 1 Report (IPCC, 2021) includes five illustrative scenarios, the most ambitious of which (SSP1-1.9) will still very likely result in average global surface temperature over 2081–2100 being higher by 1–1.8°C compared to 1850–1900. This scenario utilises BECCS to remove 5 Gtpa by 2050.
- In IRENA's 1.5°C Scenario, BECCS use results in 2.7 Gtpa of CO_2 captured and stored in 2040, and 4.5 Gtpa of CO_2 in 2050 (Figure 13). This includes the carbon balance in the chemical and petrochemical industry through carbon stocks in chemical products, recycling and carbon capture in waste incineration. As a result, towards 2050 the power and industry sectors become net negative; i.e. the CO_2 captured more than compensates for remaining CO_2 emissions in those sectors. To capture 4.5 Gtpa of CO_2 by 2050 would require investments of more than USD 1.1 trillion between 2021 and 2050 (IRENA, 2021a).
- BECCS can, in principle, be utilised in a range of processes but the optimum application of BECCS requires more detailed investigation of costs, logistics and sustainable biomass supply chains, and will be highly country and context specific. IRENA's 1.5°C Scenario includes biomass-based processes from which 10.12 Gtpa could be captured and stored by 2050 (see Table 1). Of that potential, the scenario assumes 44% (4.5Gtpa) is actually captured and stored but is not specific about where BECCS would be applied. The most significant opportunities are in power, heat, chemicals and biorefineries but BECCS could also be significant in cement, pulp and paper, and food production. The potential in iron and steel production is low in the 1.5°C Scenario by 2050, since the scenario assumes a nearly complete transition away from blast furnaces by then, but the BECCS potential could be larger there during the transition or if more blast furnaces utilising biomass and CCS are retained.
- To illustrate the scale of BECCS required, the Drax power plant in the UK has converted four coal-fired units (each rated at c. 660 MW) to biomass and is planning to retrofit CCS to at least two units (Drax, 2020). Each individual unit would capture circa 4 Mtpa. Capturing 4.5 Gtpa would require over 1100 such units around the world, or an equivalent, and most BECCS applications will be much smaller than this. Annex B section 2.3 and Annex F section 6.1 discuss the role of BECCS in more detail.

TABLE 1: Potential for biogenic carbon capture in 2050 in IRENA's 1.5°C Scenario

Process group	Biogenic carbon capture potential in 2050
	$GtCO_2$
Power	4.43
Heat	1.29
Cement	0.37
Iron and steel	0.03
Chemicals	1.18
Pulp and paper	0.35
Food sector	0.30
Biorefinery	2.15
Total	**10.12**

FIGURE 13: Share of BECCS by sector in 2050



- BECCS capture capacity in 2021 is c. 0.001 Gtpa (1 Mtpa) of CO_2. There are currently three operating commercial plants and an additional seven commercial plants are at different stages of development that would add circa 0.007 Gtpa (7 Mtpa) of CO_2 capture capacity when operational. In addition, 19 pilot and demonstration projects are either in different stages of development, completed or in operation (Geoengineering Monitor, 2019, 2021; NASEM, 2019; Viebahn, Scholz and Zelt (2019).
- Based on current applications, cost estimates for CO_2 capture have a very wide range, including: USD 12–22/tCO_2 for bioethanol production; c. USD 64/tCO_2 for coal-fired power plants with 10% biomass co-firing; USD 157–188/tCO_2 for 100% biomass power plants using white wood pellets; and USD 87–104/tCO_2 for cement production with 30% biomass co-firing (Consoli, 2019; IEAGHG, 2019a; IRENA and Methanol Institute, 2021; Khorshidi et al., 2016; Mandova et al., 2019; Szczeniak et al., 2020; Sanmugasekar and Arvind, 2019).

Other CDR technologies such as DACCS require further development and validation before their role can be evaluated.

- Other CDR technologies include DACCS and some other approaches that are mostly at an early experimental stage, which makes their future potential hard to quantify. According to this early experience, projects face high energy and land requirements, but offer flexibility in terms of their location.
- DACCS is another CDR technology that is in the early stages of development and a long way from reaching the gigatonne-scales needed to be impactful. There are two commercial plants currently operating and capturing a negligible amount of CO_2 (0.0009 Mtpa, 0.9 ktpa), and one other plant is under development and would add an additional 0.021 Mtpa (21 ktpa) of CO_2 capture. In addition, there are 15 pilot and demonstration plants – three completed, seven in operation and five at various stages of development (Geoengineering Monitor, 2019, 2021; NASEM, 2019; Viebahn, Scholz and Zelt, 2019).
- These technologies do not currently play a major role in the IRENA 1.5°C Scenario. However, countries and investors are beginning to make financial commitments to large-scale DACCS projects, which – if successful in driving scale – would allow DACCS to offset some of the need for BECCS or could allow for more emissions elsewhere.
- The energy requirements for DACCS differ based on technology but for all current designs they are significant. Based on current designs, around 200 TWh is required per 100 Mt of CO_2 captured. Capturing 4 Gtpa by 2050 would consume 8 000 TWh of electricity per year – about a third of the electricity use today (Sekera and Lichtenberger, 2020). However, in a 1.5°C Scenario, electricity use increases approximately three-fold to reach 70 000 TWh, so the additional use for DACCS would be a further 11%. That is an additional demand and comes on top of an already herculean scale-up in electricity supply. The implications of the large-scale use of DACCS for the global power system will be significant, therefore, but not insurmountable. Annex B section 2.2 and Annex F section 6.2 expand on DACCS.

4

ACTIONS REQUIRED IN THE NEXT 10 YEARS

Accelerated action on multiple fronts is needed, including many more projects in the 2020s, if CO_2 capture is to play a sufficient role by 2050.

- CCS, CCU and CDR technologies are established but not widely deployed, and the pace of progress in their development and deployment in the past decade has been very slow – much slower than many analysts predicted – with many plans falling by the wayside.
- There are some signs that the pace may pick up, driven by the stronger policy signals provided by the increasing ambition for deep decarbonisation; but the lessons of the slow progress to date need to be learned. These technologies are complex to deploy, capital intensive and increase operational costs. They increase the risks and costs of projects, mostly without direct benefits to their investors. Private sector actors alone are therefore unlikely to drive the accelerated pace of progress needed without much stronger incentives.
- To adequately scale the technologies will entail numerous conditions, including: a stable and well-functioning RD&D funding programme, including support for demonstration, first-of-a-kind and commercial projects; robust life-cycle analysis; an enabling regulatory framework and standards; technology-promoting institutions

FIGURE 14: Actions required in the next 10 years

Objectives for the next 10 years	10 key actions
Scale-up RD&D activities	1. Encourage public-private international RD&D activities
	2. Build demonstration, first-of-a-kind and lighthouse projects on capture, transport and storage aspects everywhere
	3. Focus on researching and understanding the public perception of carbon capture, but particularly transport and storage
Establish enabling conditions to speed up demonstration & deployment	4. Develop predictable but flexible national and cross-border policies, regulations and standards for public-private cooperation
	5. Establish and empower technology-promoting institutions and organisations
	6. Introduce and ensure access to various types of stable, balanced but dynamic financial support
	7. Implement enabling and cost-effective hub-and-cluster models
	8. Develop and ensure open access to information
	9. Speed up deployment of a large number of CCS / CCU/ BECCS/ DACCS networks with one or more heavy industry
Ensure sustainability of the process	10. Ensure sufficient and sustainable sourced biomass for BECCS and the assessment of the full life-cycle emissions in BECCS, DACCS and CCS projects

and organisations; financial incentives such as grants and tax-credit mechanisms; the active promotion of CCS technologies to the public (Romansheva and Ilinova, 2019); and, in the case of BECCS, sufficient sustainably-sourced biomass feedstock.

- Some countries and regions such as Australia, Canada, China, Norway, the United States, the United Kingdom and the European Union have invested in CCS over the past two decades, including both RD&D funding and some incentives for CCS deployment, and have started characterising commercially viable storage sites. Other countries are beginning to take an interest and put support mechanisms in place but there are still large gaps in the infrastructure, regulatory and financial landscapes.

- International co-operation will be an important enabler in leveraging national efforts, sending consistent signals to investors and promoting widespread sharing of experiences and lessons learned from early deployments. Such co-operation must reach beyond the front-running countries to ensure all nations have the knowledge and capacity to plan for the adoption of emerging technologies.
- Setting clear, feasible but ambitious national and international goals can be a powerful tool for building consensus and informing shared action plans. A very important recent example of this approach that is gaining widescale backing from diverse global stakeholders is the UN Race-to-Zero Emissions Breakthroughs initiative.[9] The initiative sets out near-term goals for more than 20 sectors and aims to inform a master plan around which business, government and civil society can unite; its diverse goals call for (Climate champions, 2021):
    - The establishment of over 50 new CCS and CCU networks by public and private actors, reaching final investment decisions (FID) by 2026 and totalling 400 Mtpa in new capacity. Each network should include one or more heavy industry participants. The end goal is for heavy industries to achieve net-zero emissions by 2050 and a fully decarbonised global electricity system by 2040.
    - Public commitments to capture 100 Mtpa by 2030 using engineered solutions for carbon removal (e.g. BECCS and DACCS). The end goal is for over 5 Gtpa of CO_2 removal and storage capacity operational by 2050.
- Shared goals such as these are a valuable starting point but the next step is to create coalitions of actors developing and implementing shared plans to deliver these goals. Some national and cross-border initiatives to achieve aspects of the above are emerging, particularly around building hub-and-cluster models and shared transportation networks, but their scale falls far short of what is needed.

RD&D support needs to be expanded, including through cross-border collaboration.

- RD&D support mechanisms help to examine technical, environmental and economic feasibility and facilitate technology advancements, address barriers and increase confidence in the technology. Pioneering countries and regions (Australia, Canada, Norway, the United States and the European Union as a region) have established funding programmes to support RD&D in CCS in the last two decades, and the support has increased moderately in the past year or two. Particular RD&D activities that must be expanded to examine feasibilities and barriers include:
    - refined CO_2 capture technologies – particularly for industrial applications;
    - alternative options for long term storage or long-term uses of CO_2;
    - transport – refurbishing oil and gas pipelines and ships; and
    - alternative CDR options, including DACCS.
- Some past CCS projects have been halted or impacted due to a lack of public acceptance; there is a role, therefore, for research into public perceptions of CCS, particularly for onshore transport and storage. Public perception and acceptance are becoming an important precondition for large-scale deployment of CCS, while CCU generally enjoys broader public acceptance. How the public perceives CCS depends on the sources and forms of information, and on the framing of policies that support CCS (UK CCS, n.d.). Therefore, an early understanding of stakeholders' perceptions of CCS needs to be established and followed by with inclusive and open stakeholder engagement.

9 https://racetozero.unfccc.int/join-the-race/

Many more large-scale demonstrations, first-of-a-kind (FOAK) and lighthouse projects need to be established in multiple regions of the world.

- Whilst the technological principles of CCS, CCU and CDR are proven, there remains substantial scope for technology refinement and much to learn about both their practical applications in different contexts, and the economic and wider societal implications of their use.
- The priority in the 2020s must be to establish many more large-scale demonstrations, FOAK and lighthouse deployments with extensive analyses, and the wide sharing of the experience acquired in order to build up both the knowledge base and confidence of policy makers and investors.
- Priorities for such projects include:
  - BECCS for power production, cement and chemicals production;
  - CCS for steel production;
  - CCS and CCU in the chemical sector;
  - CCS for blue hydrogen production;
  - long-term geological storage of CO_2, with appropriate monitoring and verification; and
  - hubs and clusters of CCS, CCU and CDR projects with shared transportation and storage infrastructures.

Assessments of the role and value of CCS projects must consider full lifecycle emissions.

- Analyses of CCS, CCU and CDR projects need to consider lifecycle emissions – particularly upstream emissions. These are from fuels and materials, as well as the preparation of the chemicals used in the capture and manufacture of CCS equipment/technologies, and the differences can be substantial. Based on the IPCC Assessment Report AR5, direct emissions from a coal power plant with post-combustion capture accounts for 120 $kgCO_{2eq}$/MWh, while lifecycle emissions account for 220 $kgCO_{2eq}$/MWh; in the case of a natural gas combined cycle power plant with CCS, the direct emissions are around 57 $kgCO_{2eq}$/MWh but lifecycle emissions account for 170 $kgCO_{2eq}$/MWh (IEAGHG, 2019a). In the case of BECCS, the lifecycle emissions calculation is even more complex, with potential uncertainties around the CO_2 implications of the biomass supply chain.
- A key metric for assessing CCS projects should be "avoidance efficiency", which includes factors such as upstream emissions, the energy and efficiency penalty for CCS use, and underground CO_2 retention, and which requires further research, refinement and communication.

For BECCS, biomass feedstocks need to be sourced in a proven environmentally and socially just way.

- To source biomass sustainably requires a detailed assessment and development of supply chains for the sustainable supply of biomass in specific national and sectorial contexts.
- The CO_2 produced from biomass can only be considered neutral to the atmosphere if the source of biomass is continually renewed as the biomass is harvested, and if its use does not cause other negative land-use changes. The time scale for regrowth of biomass also matters for a 1.5°C Scenario; utilising biomass that takes decades to be replaced may not be consistent with the 1.5°C degree goal.

- The sourcing of biomass must also address wider sustainability risks – i.e. it should not cause other environmental, economic or social harms such as land-use change or competition with food supply. The use of biomass in the energy transition is viewed as contentious by some, with the risk of net-deforestation being highlighted. Such concerns need to be addressed and the sourcing of biomass requires careful management to mitigate those risks. Uncertainties also remain around the optimum use of finite biomass resources and further work is needed. Current estimates suggest that, with care, sufficient biomass can be sourced sustainably to allow for a significant global use of BECCS.

Predictable but flexible national and cross-border sectorial policies, legal frameworks and standards are critical to building shared public- and private-sector efforts.

- Government policies are an essential driver for CCS, CCU and CDR deployment, and can provide support through emission reduction targets, carbon pricing and financing commitments.
- Both national and cross-border sectorial plans are needed to build a shared public- and private-sector understanding of the roadmap for CCS, CCU & CDR uptake in a given sector. Such roadmaps need to clearly distinguish between different technologies and give careful consideration to the appropriate role of each technology in that sector.
- The development of suitable legal frameworks for CCS is critical, particularly for storage. It needs to be clear and predictable but also flexible, owing to the unique characteristics of each project/plant. Regulations should focus on administration and permits (in terms of storage, for the operation of storage and access to the subsurface) across the project lifecycle and address necessary standards to protect the environment and human health through environmental impact assessments, public consultations, mandatory monitoring schemes, environmental emergency plans and long-term liability studies.
- Countries use accounting rules to track their emissions. While these rules currently include CCS and BECCS, they need to be expanded to include DACCS. In this context, the European Commission is designing a mechanism to certify nature-based and technological carbon removal solutions to provide incentives for market uptake (Tamme, 2020).
- Risk and liability particularly associated with transportation, injection and storage have been identified as critical barriers to scale up CCS deployment. Some of the traditional risks and liability provisions and models have been adopted from oil and gas operations, but the storage aspects are becoming a novel risk, exposing a still limited knowledge and experience of the industry.
- Some regulatory frameworks have begun to address these points by introducing early liability models to decrease risk, and increase insurability and confidence in CO_2 projects (Havercroft, 2019). However, further consideration of the role of public and private actors (operators and investors) in allocating and managing risks is critical, as is the engagement of the insurance sector.

Access to various types of stable, balanced but dynamic financial support is key for rapid deployment.

- As most CCS, CCU and CDR plants do not bring direct commercial benefits to investors and typically increase CAPEX and OPEX, some form of financial incentive is crucial for their deployment. Past support schemes have been complex and often not been sustained. Countries therefore need to create stable, balanced but dynamic financial support to improve confidence of the private sector; for example, in the form of tax credits, grants or loan guarantees.

- Learning from the experiences of others can help. A notable example relevant to CCS is the US Section 45Q that offers tax credits to federal taxpayers who capture CO_2 emissions of at least 25 000–500 000 tpa CO_2 for utilisation, 100 000 tpa in industrial CCS and DACCS or 500 000 tpa CO_2 from electricity generation, and either utilise (including via EOR) or store CO_2 in geological formations. Projects must commence construction by 1 January 2026, and tax credits will be available for 12 years to provide more certainty for investors. The credit value is USD 50/tCO_2 for CO_2 destined for geological storage and USD 35/tCO_2 for EOR or utilisation (US IRS, 2021).
- In 2019, California also recognised CCS and DACCS as methods of reducing the carbon intensity of fuels (measured in grams of CO_2 equivalent) and included transportation fuels whose whole lifecycle emissions have been reduced through CCS/DACCS with geological storage into the Low Carbon Fuel Standard (LCFS) scheme (Global CCS Institute, 2019).
- In the European Union, the European Commission's Innovation Fund (previously NER 300 programme) provides grants to highly innovative technologies and big flagship projects at commercial scale, regardless of their size. In addition, the European Investment Bank (EIB) Project Development Assistance increases the investment readiness of CCS projects in order to receive funding from the Innovation Fund. The EU also offers public grants under the European Research Framework programmes (e.g. Horizon 2020 or Horizon Europe), such as CEMCAP or LEILAC CCS projects in the cement industry. In addition, Project of Common Interest (PCIs) for cross-border CCS transport networks, such as the Athos or Northern Lights projects, have received PCI status and are eligible to apply for the Connecting Europe Facility (EC, 2019).
- The United States' Department of Energy offers such loan guarantees for FOAK commercial scale deployments for CCS, CCU and CDR (incl. DACCS) for up to 80% of total project costs (Holland and Knight, 2020). In the European Union, the EIB offers InnoFin Advisory services to companies on project structure to improve their access to finance, and offers numerous options for funding, including corporate loans, project finance and venture debt.
- Examples such as these will likely drive some CCS, CCU and CDR deployment but such mechanisms need to be broadened to other countries and expanded to address emerging demand.

REFERENCES

Alcalde, J., et al. (2018), "Estimating geological CO_2 storage security to deliver on climate mitigation," *Nature Communications*, Vol. 9, https://doi.org/10.1038/s41467-018-04423-1.

Bui, M., et al. (2018), "Carbon capture and storage (CCS): the way forward", *Energy & Environmental Science*, Vol. 11, pp. 1062–1176, https://doi.org/10.1039/C7EE02342A.

Climate champions (2021), "Upgrading our systems together. A global challenge to accelerate sector breakthroughs for COP26 - and beyond", https://racetozero.unfccc.int/wp-content/uploads/2021/08/2020-_Breakthroughs-Upgrading-our-sytems-together.pdf.

Drax (2021), "Drax and Mitsubishi Heavy Industries sign pioneering deal to deliver the world's largest carbon capture power project", www.drax.com/press_release/drax-and-mitsubishi-heavy-industries-sign-pioneering-deal-to-deliver-the-worlds-largest-carbon-capture-power-project.

Drax (2020), *Annual report 2019*, UK: Drax, www.drax.com/wp-content/uploads/2020/03/Drax_ AR2019_Web.pdf.

EC (2021), "Cordis EU research results database", European Commission, https://cordis.europa.eu/project.

EC (2019), "Commission publishes 4th list of Projects of Common Interest - making energy infrastructure fit for the energy union", https://ec.europa.eu/info/news/commission-publishes-4th-list-projects-common-interest-making-energy-infrastructure-fit-energy-union-2019-oct-31_en.

Freitas, R.A. (2015), *The Nanofactory Solution to Global Climate Change: Atmospheric Carbon Capture*, IMM Report 45, Palo Alto, CA, USA: Institute for Molecular Manufacturing, http://www.imm.org/Reports/rep045.pdf.

Gao, L., et al. (2011), "Cost analysis of CO_2 transportation: Case study in China", *Energy Procedia*, Vol. 4, pp. 5974–5981, https://doi.org/10.1016/j.egypro.2011.02.600.

Gielen, D., et al. (2021), "18 energy transition scenarios to watch: Where they agree and disagree", *Energy Post Weekly*, https://energypost.eu/18-energy-transition-scenarios-to-watch-where-they-agree-and-disagree/.

Global CCS Institute (2020a), *Global Status of CCS: 2020*, www.globalccsinstitute.com/resources/global-status-report/.

Global CCS Institute (2019), *The LCFS and CCS Protocol: An overview for policymakers and project developers*, Melbourne, Australia: Global CCS Institute, www.globalccsinstitute.com/wp-content/uploads/2019/05/LCFS-and-CCS-Protocol_digital_version.pdf.

Harris, N.L., et al. (2021), "Global maps of twenty-first century forest carbon fluxes", *Nature Climate Change*, Vol. 11, pp. 234–240, https://doi.org/10.1038/s41558-020-00976-6.

Havercroft, I. (2019), *Lessons and Perceptions: Adopting a commercial approach to CCS liability*, Global CCS Institute, www.globalccsinstitute.com/wp-content/uploads/2019/08/Adopting-a-Commercial-Appraoch-to-CCS-Liability_Thought-Leadership_August-2019.pdf.

Hills, T.P., M.G. Sceats and P.S. Fennell (2019), "Applications of CCS in the Cement Industry", In M. Bui and N. Mac Dowell (Eds.) *Carbon Capture and Storage*, Chapter 10, https://doi.org/10.1039/9781788012744-00315.

Hills, T., et al. (2016), "Carbon Capture in the Cement Industry: Technologies, Progress, and Retrofitting", *Environmental Science & Technology*, Vol. 50, No. 1, pp. 368–377, https://doi.org/10.1021/acs.est.5b03508.

IEA (2021), *Net Zero by 2050: A Roadmap for the Global Energy Sector,* International Energy Agency, www.iea.org/reports/net-zero-by-2050.

IEAGHG (2019a), *Towards Zero Emissions CCS in Power Plants Using Higher Capture Rates of Biomass*, https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/951-2019-02-towards-zero-emissions.

IEAGHG (2019b), *Further Assessment of Emerging CO_2 Capture Technologies for the Power Sector and their Potential to Reduce Costs*, https://ieaghg.org/ccs-resources/blog/new-ieaghg-technical-report-2019-09-further-assessment-of-emerging-co2-capture-technologies-for-the-power-sector-and-their-potential-to-reduce-costs.

IEAGHG (2017), *Techno-Economic Evaluation of HYCO Plant Integrated to Ammonia / Urea or Methanol Production with CCS, https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/785-2017-02-hyco-plant-with-nh3-or-meoh.*

IEAGHG (2013a), *Iron and Steel CCS Study (Techno-economics of Integrated Steel Mills), https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/1001-2013-04-iron-and-steel-ccs-study-techno-economics-integrated-steel-mill.*

IEAGHG (2013b), *Deployment of CCS in cement industry*, https://ieaghg.org/docs/General_Docs/Reports/2013-19.pdf.

IPCC (2021), *IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Intergovernmental Panel on Climate Change, Cambridge University Press, www.ipcc.ch/report/ar6/wg1.

IPCC (2011), *IPCC Expert Meeting on Geoengineering*, meeting report, Lima, Peru, https://archive.ipcc.ch/pdf/supporting-material/EM_GeoE_Meeting_Report_final.pdf.

IPCC (2005), "Underground geological storage", In *Carbon dioxide capture and storage*, Chapter 5, IPCC Switzerland, www.ipcc.ch/report/carbon-dioxide-capture-and-storage/.

IRENA (2021a), *World Energy Transitions Outlook: 1.5°C Pathway*, International Renewable Energy Agency, Abu Dhabi.

IRENA (2021b), *Renewable Power Generation Costs in 2020*, International Renewable Energy Agency, Abu Dhabi.

IRENA (2020), *Reaching zero with renewables: Eliminating CO_2 emissions from industry and transport in line with the 1.5°C climate goal*, International Renewable Energy Agency, Abu Dhabi.

Khorshidi, Z., et al. (2016), "Techno-economic evaluation of co-firing biomass gas with natural gas in existing NGCC plants with and without CO_2 capture", *International Journal of Greenhouse Gas Control*, Vol. 49, pp. 343–363, https://doi.org/10.1016/j.ijggc.2016.03.007.

Lena, E.D., et al. (2019), "Techno-economic analysis of calcium looping processes for low CO_2 emission cement plants", *The International Journal of Greenhouse Gas Control*, Vol. 82, pp 244-260, https://doi.org/10.1016/j.ijggc.2019.01.005.

MacDowell, N., et al. (2017), "The role of CO_2 capture and utilization in mitigating climate change", *Nature Climate Change*, Vol. 7, pp. 243–249, https://doi.org/10.1038/nclimate3231.

Mandova, H., et al. (2019), "Achieving carbon-neutral iron and steelmaking in Europe through the deployment of bioenergy with carbon capture and storage", *Journal of Cleaner Production*, Vol. 218, pp. 118–129.

MIT (Massachusetts Institute of Technology) (2016), "Carbon Capture and Sequestration Project Database", https://sequestration.mit.edu/tools/projects/, (accessed March 17, 2021).

NASEM (National Academies of Sciences, Engineering and Medicine) (2019), *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, Washington D.C: The National Academies Press, www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda.

OGCI (Oil and Gas Climate Initiative) (2020), "CO_2 Storage Resource Catalogue", www.ogci.com/co2- storage-resource-catalogue/.

Romansheva, N., and A. Ilinova (2019), "CCS Projects: How Regulatory Framework Influences Their Deployment", *Resources*, Vol. 8, No. 4, p. 181, https://doi.org/10.3390/resources8040181.

Sanmugasekar, K., and V. Arvind (2019), *Towards Negative Emissions in Cement Industry*, Delft University of Technology, https://repository.tudelft.nl/islandora/object/uuid%3A4ad209d2-7d84-4f6b-ad2c-015a81637014.

Sekera, J., and A. Lichtenberger (2020), "Assessing Carbon Capture: Public Policy, Science, and Societal Need", *Biophysical Economics and Sustainability*, Vol. 5/14, https://doi.org/10.1007/s41247-020-00080-5.

Szczeniak, J., C. Bauer and T. Kober (2020), *DEEDS Industry Database - Dialogue on European Decarbonisation Strategies*, Paul Scherrer Institute, https://deeds.eu/results/industry-database/.

Tamme, E. (2020), *Where does CCS feature in the European Green Deal?,* Global CCS Institute, www.globalccsinstitute.com/news-media/insights/where-does-ccs-feature-in-the-european-green-deal.

Toktarova, A., et al. (2020), "Pathways for Low-Carbon Transition of the Steel Industry - A Swedish Case Study", *Energies*, Vol. 13/15, p. 3840, https://doi.org/10.3390/en13153840.

UK CCS (n.d.), "CCS explained: Systems and policy", https://ukccsrc.ac.uk/ccs-explained/systems-and-policy.

US IRS (Internal Revenue Service) (2021), *26 U.S. Code § 45Q - Credit for carbon oxide sequestration*, *26 U.S. Code Title 26 - INTERNAL REVENUE CODE*, www.federalregister.gov/documents/2021/01/15/2021-00302/credit-for-carbon-oxide-sequestration.

Viebahn P., A. Scholz and O. Zelt (2019), "The Potential Role of Direct Air Capture in the German Energy Research Program - Results of a Multi-Dimensional Analysis", *Energies*, Vol. 12(18)/3443, https://doi.org/10.3390/en12183443.

Voegele, E. (2021), "Drax, Mitsubishi partner on BECCS project", *Biomass Magazine*, http://biomassmagazine.com/articles/18066/drax-mitsubishi-partner-on-beccs-project.

Volsund, M. et al. (2018), "Retrofitability of CO_2 Capture Technologies to Cement Plants", http://dx.doi.org/10.2139/ssrn.3366119.

ZEP (2011a), *The Costs of CO_2 Transport - Post-demonstration CCS in the EU*, European Technology Platform for Zero Emission Fuel Power Plants, www.globalccsinstitute.com/archive/hub/publications/119811/costs-co2-transport-post-demonstration-ccs-eu.pdf.

ZEP (2011b), *The Costs of CO_2 Storage - Post-demonstration CCS in the EU*, https://zeroemissionsplatform.eu/wp-content/uploads/CO2-Storage-Report.pdf.

ANNEXES

The following Annexes supplement the summarised discussion in the main report by providing more detailed background information, discussion of key components and tables of existing and planned projects.

ANNEX

A

CCS, CCU AND CDR, AND THEIR ROLES IN EMISSIONS REDUCTION

1.1 Carbon capture in the energy transition

In the 2015 Paris Climate Change Agreement, countries committed to striving to limit global temperature rises to well below 2°C and to reach net-zero emissions by the second half of this century. In the years since, a growing range of countries and organisations around the world have committed themselves to trying to keep temperature rises to no more than 1.5°C and to reaching net-zero emissions by mid-century.

IRENA's 1.5°C compatible scenario by 2050, as outlined in the 2021 *World Energy Transition Outlook* (IRENA, 2021a), shows that a credible but narrow pathway exists, but will require major efforts on all fronts and the use of all the decarbonisation tools in the toolbox. The use of renewables coupled with reductions in energy intensity will be the principal pillars of a net-zero pathway, accounting for 80% of emissions reductions in a 1.5°C Scenario; but they will need to be supplemented in some contexts by CO_2 capture and storage.

The 1.5°C Scenario suggests that: 52% of captured CO_2 emissions by 2050 would be captured with bioenergy with CCS (BECCS) in the power sector, cogeneration plants, as well as in industry (cement and chemicals sector); 36% of CO_2 emission reduction would be through deployed fossil-based CCS and CCU in the cement, iron and steel, and chemicals sectors; while 12% of CO_2 emissions would be captured through the production of blue hydrogen. These measures would cumulatively remove 126 Gtpa CO_2 between 2021 and 2050 (IRENA, 2021a).

1.2 The status of CCS, CCU and CDR

The suite of available technologies to capture, transport, store and utilise CO_2 are at varying technology readiness levels (TRLs) (Box 3). Some technologies are at the mid-TRL requiring further RD&D support, while many technologies are at a higher TRL and require financial investment and commercial interest to scale up their deployment (Bui et al., 2018).

As of March 2021, 24 commercial fossil fuel-based CCS and CCU facilities are in operation globally, with an installed capacity to capture around 0.04 Gtpa of energy and process-related CO_2 emissions, representing about 0.1% of global CO_2 emissions (Consoli, 2019; EC, 2021; Global CCS Institute, 2020a; IRENA, 2020; MIT, 2016). Actual capture is lower than installed capacity and has risen to about 90% of its potential over the years (Garcia Freites and Jones, 2020).

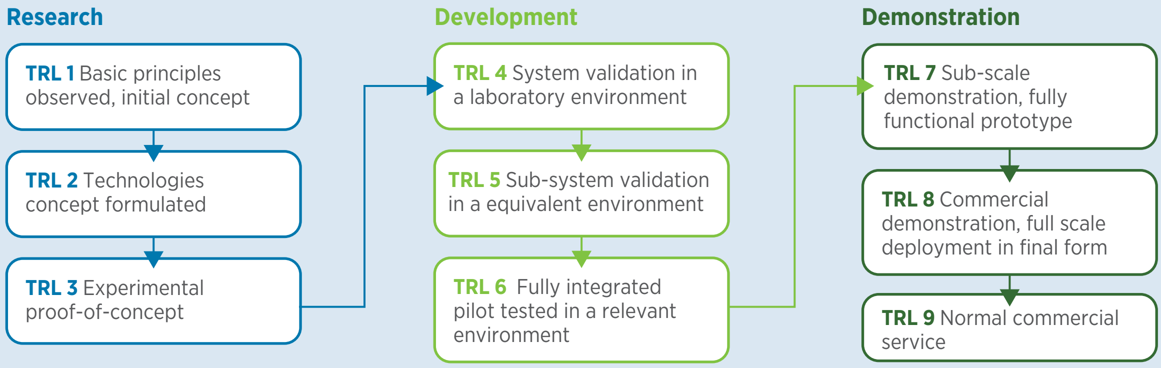
Of these CCS and CCU facilities, 11 are natural gas processing plants (where CO_2 needs to be removed anyway to produce natural gas that meets specific standards) and one is a coal-fired power plant. Chemical plants – mostly for ethanol production, hydrogen production in refineries and in iron and steel plants account for the remainder (Figure 15). Three plants were operational but are now closed or suspended and an additional 30 commercial plants are at various stages of development. A further 24 smaller-scale pilot and demonstration plants have been completed, 16 are operating and 19 are at various stages of development. If all commercial plants under development are completed, capture capacity would rise to approximately 0.1 Gtpa.

There are currently three operational commercial facilities that use bioenergy with CCS (BECCS) and six commercial plants in development. Current capture capacity of operational commercial BECCS plants is very small, at 1.13 Mtpa, which would rise to 7.86 Mtpa if all plants under development reach operation. A further nine small-scale pilot and demonstration BECCS plants are operation; five are completed and three are at different stages of development.

There are two facilities that use direct air capture with storage (DACCS), with one in development, plus 15 pilot and demonstration plants are in operation or development; however, collectively, their capture capacities are negligibly small.

BOX 3: Technology readiness level

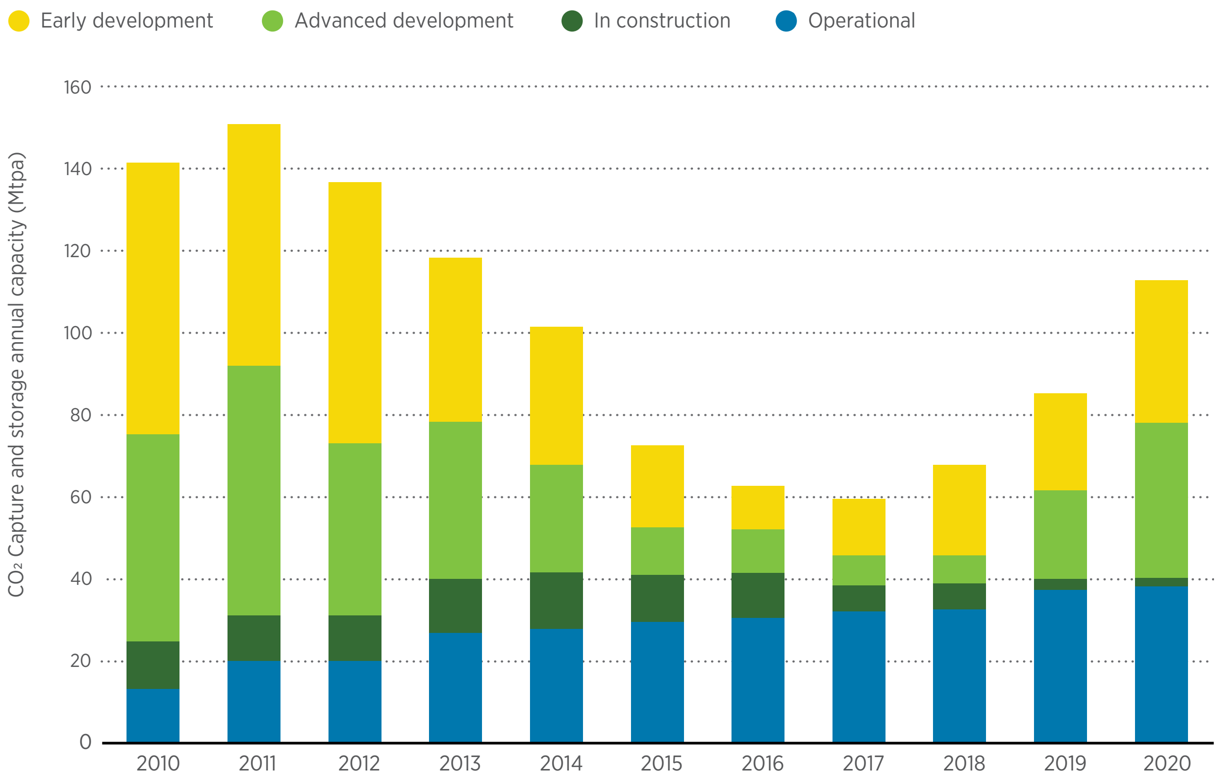
Technology readiness level (TRL) is a widely used measure of the maturity level of a technology. TRLs range from 1 to 9, with TRL 1 referring to the beginning of scientific research, and TRL 9 referring to a proven technology that is commercialised. The overview below is the EPRI adaption for post-combustion technologies.



Source: Adapted from EPRI (Freeman and Bhown, 2011).

Despite the IPCC reports (2005, 2014 and 2018) assigning significant emissions reduction potential to CCS, CCU and CDR, progress in the deployment of CCS, CCU, BECCS and DACCS projects has been very slow. The exception has been capturing CO_2 from natural gas processing and its use for enhanced oil recovery. The installed capacity only doubled between 2010 and 2020 from 0.02 Gt to 0.04 Gt of annual captured CO_2.

Figure 15: CCS plants, 2010–2020



The capacity of facilities where operation is currently suspended is not included in the 2020 data.

Source: (Global CCS Institute, 2020a).

1.3 Understanding the current costs of CCS, CCU and CDR

The costs of CCS, CCU and CDR will be a crucial factor in decisions on its future role. Cost components of capture, transport and storage are discussed in the respective chapters. This chapter highlights some general underlying uncertainties associated with the costs of these components and explores relevant terminology.

Cost estimates vary widely, with future projections having a high degree of uncertainty. CCS facilities are capital intensive and, in general, capture costs dominate, but in some cases CO_2 transportation costs can be significant. Actual costs are site-specific and differ significantly depending on the technology used, the distance from the storage site, as well between sectors (CO_2 volume, CO_2 concentration and pressure).

Cost estimates in literature are broad, with many inconsistencies in approach. When discussing and comparing costs, the project specifics and the full end-to-end project costs need to be examined. Factors that need to be considered include:

- Whether the quoted cost is the *cost per tonne of CO_2 avoided* or *cost per tonne of CO_2 captured* or – in case of CDR – *cost per tonne of CO_2 removed*. As CCS entails additional energy use, it results in additional CO_2 emissions. The difference can be 10–25%. Cost per tonne of CO_2 avoided is the best measure to compare with renewable options. It can also be used to compare different capture technologies across different sectors and in learning curves.
- The calculated costs of feasibility studies tend to be much lower than the cost of actual projects that have been implemented. Many of the actual projects have witnessed significant costs overruns.
- CCS proponents claim significant potential for learning effects and foresee significant cost reductions going forward. It is difficult to validate such claims but, given the limited deployment to date and experience with other technologies, cost reduction through learning and economies of scale is likely.
- Many cost estimates in the literature focus only on capture costs and either ignore costs for compression/liquefaction, transportation and storage (including assessment and monitoring cost) or treat transport and storage as lump sums, disregarding costs for the flowrate, distance to storage or utilisation site, or storage type.
- Many estimates are theoretical and have assumptions that are prone to change during live projects. Therefore, several estimates, as helpful as they are, can only give a sense of costs associated and not the actual costs for delivering reduced or negative emissions.
- Cost estimates tend to consider large-scale CCS facilities with large CO_2 volumes (such as gas plants), that can justify dedicated transport and storage infrastructure, but disregard smaller, mostly industrial plants that emit lower CO_2 volumes per year (such as cement plants), and will therefore have to rely on clusters, hubs and transportation networks to benefit from economies of scale. The difference in cost could be a factor or two.
- Costs for BECCS tend to include those of sourcing and transporting biomass, and include life-cycle emissions related to both direct and indirect land-use that results in a 10–30% energy penalty, even if biomass is derived from land dedicated to biomass crops or cellulosic sources (Fuss et al., 2018). This makes comparing CCS and BECCS more complex.

1.4 Debates about the future role of CCS, CCU and CDR

Debates about CCS

CCS is a contentious topic in discussions about energy transitions and climate change mitigation, with opinions on its role often starkly divided. The debate pivots around three key points: the continued use of fossils fuels, future costs of CCS relative to alternatives, and overall effectiveness. Opponents argue that CCS perpetuates the continued use of fossil fuels and is expensive, unproven at scale, unnecessary and not sufficiently effective. Proponents argue that CCS allows the continued use of existing (fossil fuel-based) processes and infrastructure, and/or is essential in some circumstances, and will become more effective and economic given time and support to scale.

1. **The use of fossil fuels**: both proponents and opponents see CCS as perpetuating the use of fossil fuels but differ as to whether that is a positive or negative. Opponents argue it is better to wean the world off a polluting energy source and adopt cleaner alternatives. They see the use of CCS as allowing for continuing existing polluting practices and that the prospect of later CCS retrofits allows polluting plants to continue to operate and new such plants to be built, thus increasing emissions now without guaranteeing the eventual decommissioning or retrofit. Proponents argue that using CCS with fossil fuels will be less disruptive to established systems than switching completely to alternatives, and allows current jobs and the value of past investments to be retained.

2. **Investments and future costs**: opponents highlight current high costs and the low deployment rates of CCS to date, and uncertainties around costs in the future. They also note that the large scale of investment and public subsidy needed risks detracting from other clean energy investments. CCS is capital intensive, requiring large up-front investments in both capture plants, and CO_2 transportation and storage infrastructure, and – due to the lack of commercial incentives – is likely to require some public subsidy or incentives. Proponents, however, argue that there have been limited incentives to invest in CCS to date, but that the net-zero goal changes that, and costs will fall as deployment scales, as has been the case with other technologies – notably solar and wind.
3. **Effectiveness in reducing emissions:** opponents point out that capture technologies are not 100% effective. Capture efficiencies vary significantly by sector and project but are usually quoted to be in the region of 80–95%. However, higher levels, in some cases approaching 99%, are technically possible, albeit at higher costs. In addition, other stages in the processes carry risks of emissions, including from: the energy-use involved in extracting and transporting fossil fuels; methane emissions from oil and gas extraction; processing and transportation; and the uncertain risk of leakages from CO_2 transport and storage. If net-zero emissions are the goal, then any remaining emissions need to be offset by increased carbon dioxide removal measures elsewhere. Proponents acknowledge that CCS is not 100% effective but argue that high capture rates are possible, the remaining emissions are manageable with care, and the risks of leakage are negligible.

Those debates are not likely to be resolved soon. In practice, the eventual role of CCS will depend on a complex mix of geopolitics, the attitudes of societies and decisions makers, economics, and technology progress (both in CCS and alternatives). The balance of opinion currently is that there is some role for CCS; the debate, therefore, is about the scale and specific roles of CCS.

It is likely that CCS will play a role in the world's decarbonisation pathway for a variety of reasons. The principal reason is that reaching net-zero by 2050 is going to require every tool in the decarbonisation toolbox. The accelerated adoption of renewables, alongside aggressive reductions in energy intensity, can deliver most of what is needed but is unlikely to be scaled quickly enough to address all emissions. Some fossil fuel use will remain by 2050. Secondly, for some processes (particularly cement), sufficiently effective and scalable alternative decarbonisation options do not exist and are not currently on the horizon. Thirdly, CCS is integral to some CDR methods such as BECCS and DACCS that are needed to deliver the negative emissions that allow a balanced net-zero energy system. Finally, some governments will opt to use CCS, in part because it allows them to continue using fossil fuel resources or because it provides a cost-effective option to utilise existing assets – out of 19 long-term low-GHG emission development strategies (LEDS) under the United Nations Framework for Convention on Climate Change (UNFCCC) submitted in November 2020, 15 included the use of carbon capture with mentions of BECCS and DACCS.

Debates about CCU

Many of the same arguments discussed above for CCS apply to CCU, but with the added dimension that some uses of CO_2 lead to the eventual release of that CO_2 to the atmosphere. If that CO_2 has been captured from fossil fuel processes, its eventual re-release adds to the net-levels of CO_2 in the atmosphere. In the short term, if CO_2 utilisation avoids some other CO_2 emitting process, it has some value; but in the long term, with a net-zero emissions goal, such usages must be eliminated. Some forms of utilisation lock away the CO_2 for an extended period of time. Such uses are effectively a form of storage and so are subject to the same arguments and trade-offs as CCS. However, mitigating the risk of the eventual release of the CO_2 still requires careful management.

The other aspect of CCU, as is the case for CCS, is limited commercial benefits for investors. As there is some profit from utilisation, it is of interest of investors and industry. Supporting CCU in short term may drive the scale-up of CO_2 capture technologies and in turn push costs down. But that requires policies, regulations and access to finance in the form of tax credits or loan guarantees.

Debates about CDR

Debates on the role of CDR are slightly less contentious, with the main concern being the moral hazard of the potential for the later use of CDR being used as an excuse for less urgency in emission reductions now. There are also debates about the extent to which net-zero strategies can, and should, rely on CDR as a core component or hold it back as an insurance policy against underperformance in other areas.

The main challenges with BECCS are similar to CCS: BECCS is not yet fully proven in end-to-end processes; there are operational implications for the installation of CCS; costs are currently high; and the cost reduction potential is uncertain. In addition, BECCS also introduces the challenge of ensuring sufficient, sustainably-sourced biomass. The degree to which biomass use impacts emissions depends on the biomass supply chain, the source of biomass must be continually renewed as the biomass is harvested, and its use should not cause other negative land-use changes. The time scale for regrowth of biomass also matters for a 1.5°C Scenario, as utilising biomass that takes decades to be replaced may not be consistent with this goal.

The sourcing of biomass must also address wider sustainability risks, i.e. it should not cause other environmental, economic or social harms such as land-use change or competition with food supply. The use of biomass in the energy transition is therefore viewed as contentious by some, with the risk of net-deforestation being particularly highlighted. Such concerns must be addressed, and the sourcing of biomass requires careful management to mitigate those risks. Uncertainties also remain around the optimum use of finite biomass resources and further work is needed in this regard. However, current estimates suggest that, with care, sufficient biomass can be sourced sustainably to allow for a significant global use of BECCS (IRENA, 2021a).

DACCS is another CDR technology that is in the early stages of development and a long way from reaching the gigatonne-scales needed to be impactful. Current commercial plants are capturing a negligible amount of CO_2 (0.0009 Mtpa). Deployment to scale up DACCS faces barriers, particularly in terms of energy, material or water requirements (NASEM, 2019).

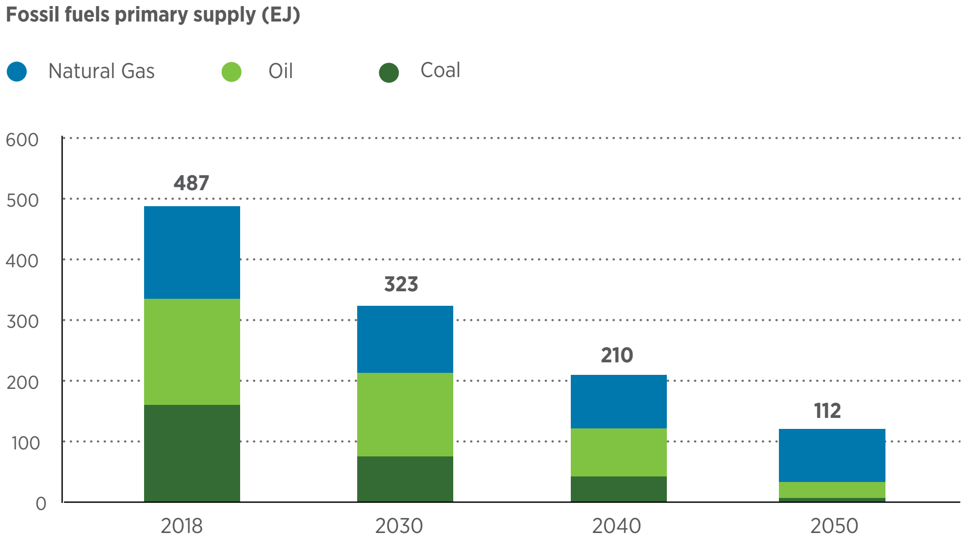
1.5 CCS, CCU and CDR in 1.5°C Scenarios

In IRENA's 1.5°C Scenario, fossil fuel production declines by more than 75% by 2050, with total fossil fuel consumption continuously declining from 2021 onwards (Figure 16). The remaining fossil fuel use is mainly in power and industry, providing 19% of primary energy supply in 2050. Oil and coal decline fastest, while natural gas peaks in around 2025 and declines thereafter. Natural gas is the largest remaining source of fossil fuel in 2050 (70% of total fossil fuel supply) at around 52% of today's level. Around 70% of the natural gas is consumed in power and heat plants, and blue hydrogen production, with most of the remainder consumed in industry. Coal production declines most drastically, from around 5 750 million tonnes in 2018 (160 EJ) to just below 240 million tonnes per year (7 EJ) in 2050. In the power sector, coal generation declines significantly to 55% by 2030, 75% by 2040 compared to current levels and by 2050 has been phased out. The remaining coal is largely used in industry – mostly for steel (by 2050 coal use with CCS accounts for about 5% of total steel production) and to a limited extent in chemicals production.

BECCS would play a role in capturing CO_2 from:

- power and heat generation with biomass (e.g. wood pellets, sugarcane bagasse or municipal solid waste [MSW]);
- cement kilns and iron blast furnaces where charcoal might be used as fuel;
- chemical plants where the feedstock is biomass (e.g. in bioethanol production and other bioplastics); and
- biogas upgrading where the CO_2 is separated for the production of biomethane.

FIGURE 16: The declining importance of fossil fuels (fossil fuel primary supply, 2018–2050 [EJ] in the 1.5°C Scenario)



Source: (IRENA, 2021a).

The role of **CCS and CCU** in the 1.5°C Scenario is limited to process- and fossil fuel-related emissions in cement, iron and steel production, and by 2050 would reduce CO_2 emissions by 36%, reaching an average annual capture rate of 1.5 $GtCO_2$. Production of **blue hydrogen (hydrogen with CCS)** would reduce 12% of remaining CO_2 emissions, reaching an average capture rate of 0.5 $GtCO_2$ by 2050. Together, these applications would capture on average 3 Gtpa of CO_2 by 2050, up from 0.04 Gtpa CO_2 captured today. That figure includes the carbon balance in the chemical and petrochemical sectors such as carbon stocks in chemical products, recycling or capture in waste incinerators.

The 1.5°C Scenario does not include the use of **DACCS**, given uncertainties around its pace of commercialisation. If rapidly deployed, it may offset the need for BECCS, CCS or other emission reduction measures.

1.6 CCS, CCU and CDR in climate pledges

Climate pledges, also known as Nationally Determined Contributions (NDCs), are critical to achieving the Paris Agreement's long-term goals. The NDCs represent each country's efforts to reduce national emissions and adapt to the effects of climate change. Countries are required to plan and communicate successive NDCs that they intend to make every five years. Domestic mitigation measures must be pursued in order to meet the goals of such contributions. However, in order to meet the Paris Agreement goals, a significant increase in ambition is required today, as the current pledges outlined in the NDCs fall far short of what is required. According to the IPCC, emission reduction ranges must be around 45% lower in order to meet the 1.5°C temperature goal.

As CCS is projected to play a noteworthy role in the transition to a net-zero economy, its role is also reflected in NDCs and long-term strategies, such as the national climate action plans submitted by parties to the UNFCCC outlining how they will adhere to the Paris Agreement's temperature targets. To date, 192 parties have submitted their NDCs to the UNFCCC since 2015 and CCS is mentioned in fifteen of these (UNFCCC, 2021).

While NDCs are shorter-term plans, revised every five years, long-term strategies typically include parties' plans to reach net-zero emissions by 2050. To date, 32 countries have submitted long-term strategies to UNFCCC; of these, 25 mention CCS technologies in their submissions (Table 2). The European Union's long-term strategy makes no mention of CCS, but it is mentioned in its European Green Deal.

Coverage of CCS varies significantly across these long-term strategies, ranging from minimal in some to substantial in others. Japan, Norway and the United Kingdom have been deemed countries with high ambitions, as they communicate ambitions to "demonstrate international leadership in carbon capture usage and storage" (United Kingdom), "establish its first commercial scale CCU technology by 2023 as a trigger for wider usage in view of full social adoption in 2030 and thereafter" (Japan) and "play a part in making CCS a cost-effective option to combating global climate change" (Norway).

TABLE 2: The inclusion of CCS in long-term strategies (LTS) submitted to the UNFCCC

Country	Mention of potential role of CCS in the energy transition	Mention of R&D needs	Mention of specific project or programme	Investment figures provided	Quantitative targets on CCS	Aims to be a leading country for CCS
Austria	×				×	
Belgium	×					
Canada	×		×		x	
Czechia	×				x	
Denmark	×		×	×	×	
Finland	×				×	
France	×	×[10]		x	x	
Germany	×					
Indonesia	×				x	
Japan	×	x	x			×
Latvia	×	x				
Mexico	×					
Netherlands	×					
Norway	×		×		x	×
Portugal	×					
Republic of Korea	×	x	×		x	
Singapore	×	x	x		x	
Slovakia	×					
Slovenia	x					
South Africa	×		×			
Spain	×					
Sweden	×		×	×		
Switzerland	×				×	
Ukraine	×					
The United Kingdom	×	x	×	×	x	×
The United States	×	x	x		x	

1.7 Challenges and opportunities for scaling up CCS, CCU and CDR deployment

Recent developments in the capture project pipeline and countries' net-zero commitments indicate a growing interest by the public and private sectors. There are, however, still several considerations to scale up deployment. These are caused by differences in methodological frameworks, the quality of input data on costs, metric definition, energy prices, waste heat availability, retrofit vs. new-built facilities, and plant location, among others. A majority of estimates of avoided costs look only at capture costs, while others include transport and storage, giving an uneven

10 The section is included as an Appendix.

range of estimates. In addition, cost estimates treat transport and storage as lump sums, disregarding flowrate, distance to the storage or utilisation site or a storage type, and assume a fixed cost of USD 10/tCO_2, distorting estimates (Roussanaly et al., 2021).

The relatively few commercial implementations of technology, especially in industry, creates uncertainties about performance, operation and scale-up. Even with several facilities at different stages of development, there is uncertainty over the energy consumption and cost implications of additional infrastructure. The competitive environment impedes knowledge cross-sharing of learning amongst companies and sectors. Regulations concerning the storage of CO_2 are absent, creating compliance risks. The issue of long-term liability for stored CO_2 lying with the operator slows down investments (Global CCS Institute, 2020b). This hinders the project pipeline and sometimes may lead to the cancellation of projects altogether. Only half of the projects announced in 2010 are in the pipeline today (Townsend and Gillespie, 2020). The cancellation of projects may change public perception and government support for this technology to mitigate climate change, confining it to theory rather than practice.

However, achieving carbon capture at scale in some industries is imperative for climate targets. This scale of capture, therefore, must grow rapidly, overcoming incumbents of these challenges. Several opportunities and enablers must be tapped simultaneously to allow project development and commercialisation.

Technology for carbon capture has matured over the years, however, it still suffers from fewer commercial projections owing to the risks and challenges mentioned earlier in this section. These can be minimised if the risk of developing capture technology and the post-CO_2 capture chain is inherited by a group of emitters, rather than by a single emitter. The **hub-and-cluster model** (Annex D, Box 5) represents a crucial opportunity, wherein risks are shared by different entities. Public–private partnerships can also help achieve this and have already led to the development of important milestones for scaling up. These include large-scale commercial hub-cluster network projects like the Northern lights in Norway and the Alberta Carbon Trunk Line in Canada.

Near-term investment opportunities in high CO_2 concentration can be a testing ground for scaling up the technology, including in sectors such as natural gas processing, fertilisers, and ethanol production, which represent the bulk of the project pipeline. The interest in these sectors is due to the low costs of capture and the value of CO_2 through its utilisation. While investments in these sectors will play a significant role in lowering costs, cross-fertilisation of knowledge with the 'hard-to-abate' sector is also essential. This will be important to establish the necessary practical estimates of costs, performance and operational impacts for scaling up capture in all sectors.

The growing momentum of carbon capture has not necessarily translated into robust legal and regulatory structures. Strong regulations, especially in transport and storage, are necessary pre-requisites for commercialisation. Countries that have seen pilots and demonstrations cannot reach the critical mass for commercialisation in the absence of supporting policy frameworks. These frameworks should address the complete project chain, from clarity of administrative processes, public consultation and environmental assessment, to long-term liability of transported and stored CO_2 (Havercroft, 2018).

Without urgent actions, CCS, CCU and CDR technologies will fail to deliver on climate objectives. The approach needs to focus on securing political, social and financial support, with new pilot, demonstration and commercial projects to test technologies in real-world settings. This will help to bring the discussion to local people and gauge their perceptions.

1.8 Comparison of CCS with renewables and other options/ solutions

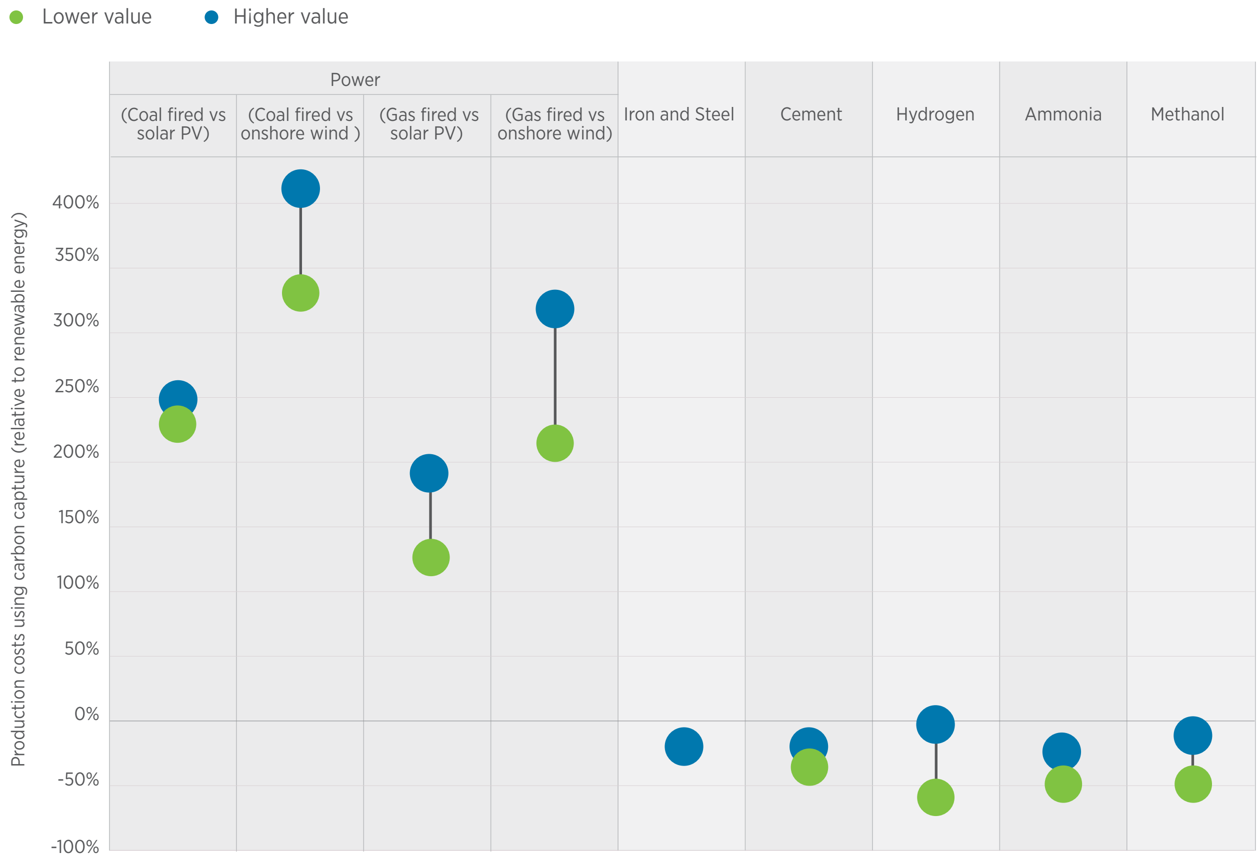
Carbon capture and renewables are two very different approaches to reducing emissions. Both have their own sets of advantages to offer and drawbacks to consider, and are often placed at opposite ends of available mitigation strategies. The debate between them is either seen through the theme of prolonging the use of fossil fuels versus shifting to non-emitting future, or through the convenience of using 'non-polluting' fossil fuels by capturing carbon.

The choice has therefore either become an ideological question or an emotional conversation, making it harder to evaluate the merits and drawbacks of both options in the context of the global energy transition.

That being said, carbon capture and renewables have different operational processes that require changes of varying significance in the workflow processes of industries and power systems. Not only does this involve some costs to accommodate these changes, but the processes are also likely to deliver different ranges of emission reductions. Therefore, the widely used 'least cost mitigation tool' criterion is too narrow for comparisons between the two approaches. Figure 17 looks at the production costs and emission reduction potentials of carbon capture technologies relative to renewables to give a fuller picture of the trade-offs of either option. It is important to reiterate that although no single technology option is sufficient to fully decarbonise most sectors, this approach can help identify 'low-hanging fruit' and must not be regarded as the "only" solution. Also, it represents either the current commercial or the most mature technology options available and can therefore change in the future as costs reduction and technologies evolve.

In the power sector, CCS use is not economically justifiable for new fossil fuel projects. The only case that can be made for its use is to utilise existing installed infrastructure; but even there, new renewable installations can deliver lower-cost power than coal plants with CCS retrofits and provide stable and often higher-wage jobs. From a current costs perspective, the use of CCS is economically justifiable for the production of hydrogen, ammonia, methanol, cement and iron, and steel (Figure 17).

FIGURE 17: Costs of production via carbon route as a percentage of renewable pathway[11]



Sources: IRENA analyses based on inputs from Lena et al., (2019); Fan and Friedmann (2021); IEAGHG (2019a, 2019b, 2019c); IEAGHG (2017a, 2017b, 2017c); IRENA (2021b).

11 Costs are current estimates.

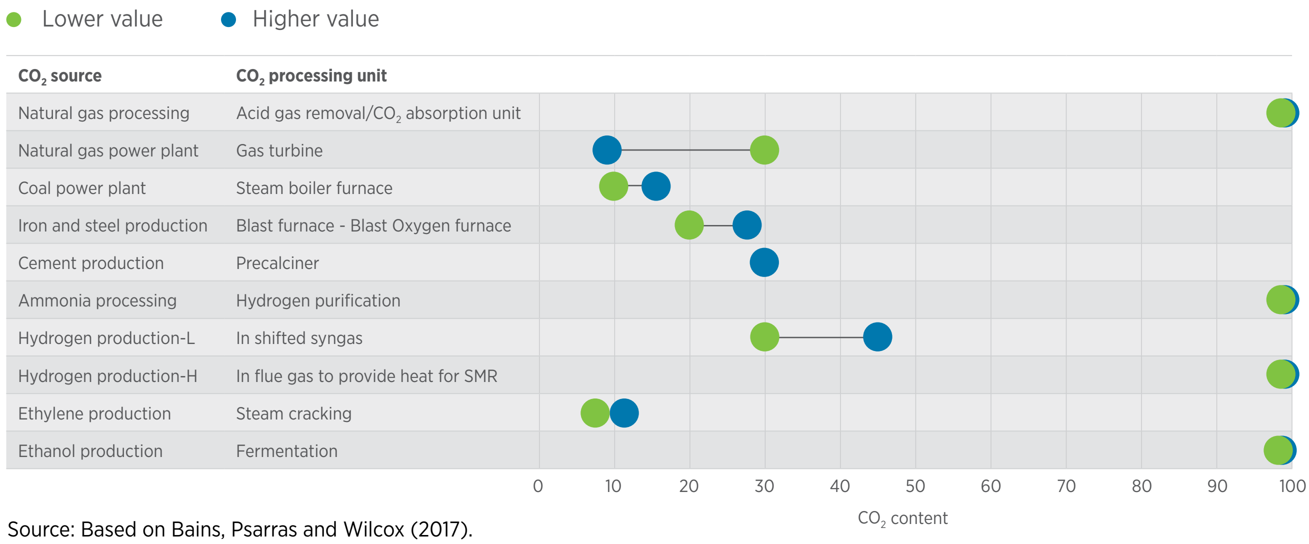
ANNEX B

CO_2 CAPTURE – STATUS AND POTENTIAL

2.1 CO_2 capture technologies for point sources

In capture processes, CO_2 is separated from flue gas or syngas in power plants or industrial processes, such as calcination in cement kilns or blast furnaces for iron production, to be later either utilised or stored underground.

FIGURE 18: CO_2 concentration per source



Source: Based on Bains, Psarras and Wilcox (2017).

CO_2 capture has a significant impact on both costs and energy consumption. The cost of capturing CO_2 from flue gas or syngas depends on its concentration (Figure 18), but also on gas quantity, pressure, contaminants and the extent to which the flue gas needs to be cleaned. Lower CO_2 content flue gas requires more energy to capture CO_2, which increases costs. The majority of operational experience to date is in natural gas processing, where the CO_2 concentration is greater than 99%, while CO_2 concentration is much lower in other industries and therefore poses additional challenges.

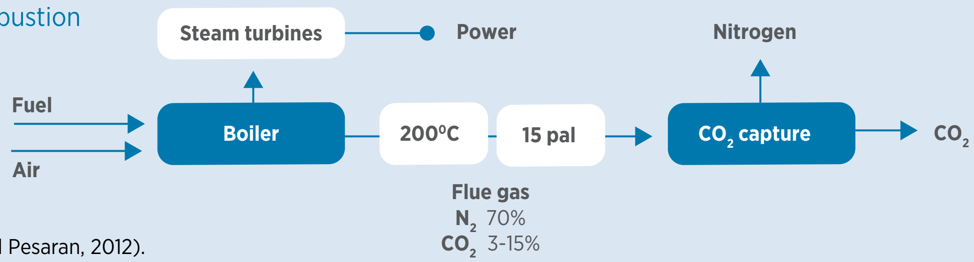
BOX 4: Three main approaches to capture CO_2

There are **three main approaches** to capture CO_2, with each approach posing distinct challenges in terms of integration into existing operations, scale-up, energy and efficiency penalty, etc.

1. Post-combustion

In post-combustion (Figure 19), CO_2 is separated and captured from the flue gases that result from fossil fuel combustion or industrial processes (e.g. calcination) using solvents, sorbents (physical and chemical) and membranes. The flue gas is a mixture of CO_2, nitrogen and oxygenated compounds (SO_2, NO_2, O_2). Once CO_2 is absorbed/adsorbed[12] by the medium, the medium is heated and produces a high purity CO_2 stream. The solvent/sorbent is then cooled and reused. The separation processes face several challenges, including as a result of impurities in flue gas, which degrade solvents or sorbents, and particularly in the case of less advanced solvents. Low levels of CO_2 in the flue gas also pose challenges. The principal advantage of the approach is that it can be applied to existing operational units, as it can be implemented at the last stage of industrial processes and therefore does not require major reengineering of existing processes. It is suitable for use in both power plants and industrial processes such as cement, iron and steel or chemical production.

FIGURE 19: Post-combustion



Source: (Vaseghi, Amiri and Pesaran, 2012).

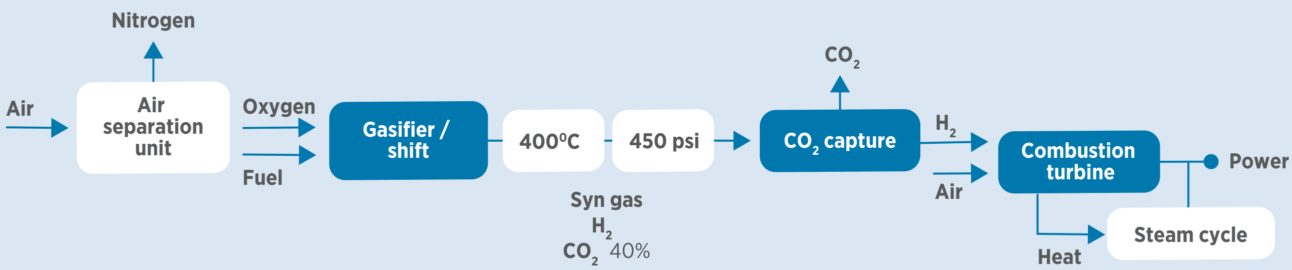
2. Pre-combustion

In pre-combustion processes (Figure 20), removal of CO_2 from fossil fuels occurs prior to combustion. The fuel is converted into syngas containing H_2, CO_2 (at around 40%), CO and smaller amounts of other gases such as methane. Hydrogen is separated and used as fuel. Compared to post-combustion, it is a more complex process and harder to apply to existing operational units. It is currently used predominantly in power plants and for

12 Absorption is the process of one material being retained by another. The medium can be in a form of a gas, liquid or solid in a liquid, vapour, a dissolved substance to a solid surface by physical forces, etc. but in the context of CCS, liquid-based solvents are used. Adsorption is the adhesion of atoms, ions and molecules from a gas, liquid or dissolved solid to the surface. The difference is that adsorption is a surface phenomenon, while absorption involves the whole volume of the material. Adsorption tends to precede absorption.

hydrogen production, and its use in industrial processes such as cement plants is limited. It may be possible only if integrated with gasification technologies to produce syngas or H_2 fuel, but this comes with additional complications, such as the low emissive power of H_2 flames, which makes them ill-suited to conventional kilns. Therefore, more efficient H_2 burners and kilns are required. On the other hand, the gaseous stream contains more concentrated CO_2, which makes it more efficient but requires higher CAPEX (US DOE, n.d.).

FIGURE 20: Pre-combustion

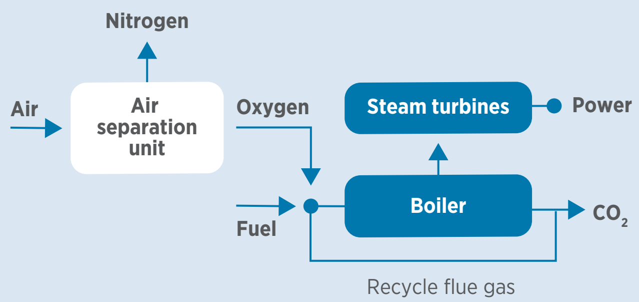


Source: (Vaseghi, Amiri and Pesaran, 2012).

3. Oxy-combustion

In oxy-combustion (Figure 21), the fuel is burned in nearly pure oxygen instead of air. The resulting flue gas contains water and CO_2, making it easy to separate by filtering O_2 from the air before burning the fuel by low-temperature dehydration and desulphurisation. Oxy-combustion recycles the flue gas to achieve lower flame temperatures to decrease energy penalty and includes lower level NO_X emissions, high CO_2 purity and lower gas volumes due to increased density (Wall, 2005). It can be relatively easily applied to both new and existing operational units, but CAPEX is higher than for other processes.

FIGURE 21: Oxy-combustion

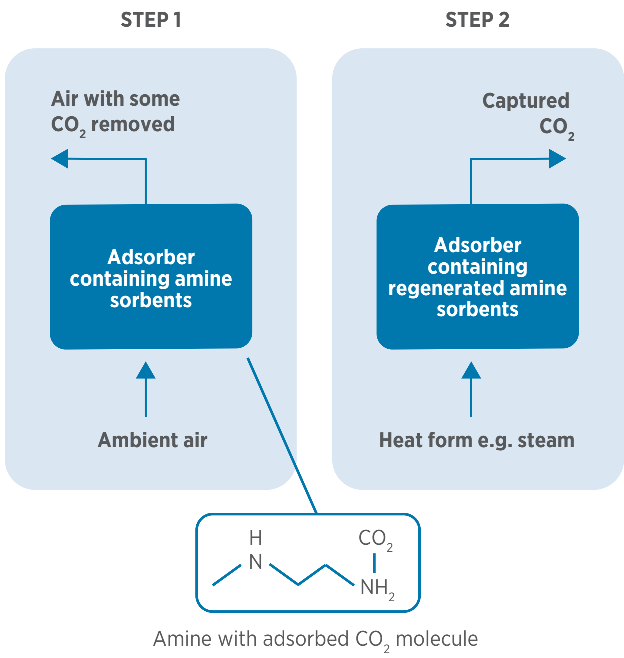


Source: (Vaseghi, Amiri and Pesaran, 2012).

2.2 CO_2 capture technologies for capture from the atmosphere

Instead of capturing CO_2 from flue gas or syngas, Direct Air Capture (DAC) technology captures the CO_2 emissions directly from the atmosphere. DAC can use various processes to scrub CO_2 from the atmosphere – chemical or cryogenic – and then separate the CO_2 for storage or utilisation. The processes resemble the post- or pre-combustion technologies, but the CO_2 source is different, and the CO_2 concentration levels are 100–300 times more dilute than the levels in coal or gas-fired power plants. The currently operating pilot, demonstration and commercial plants use chemical separation by absorption, where the CO_2 dissolves into the sorbents or adsorption as CO_2 molecules adhere to the solvent surface (Figure 22). The absorption model requires high-temperature heat to regenerate the solvent. This heat is currently mostly supplied by fossil fuels, which result only in a partial offset of emissions and add to costs per tonne of emissions avoided (Fasihi, Efimova and Breyer, 2019). The adsorption model uses low-temperature aqueous solvents, which can be supplied by heat pumps powered by renewable energy, resulting in lower costs.

FIGURE 22:
Direct air capture with chemical solvent



Source: (Gambhir and Tavoni, 2019).

The main difference between a capture facility in a power plant or an industry and DAC is the concentration of CO_2 in the input stream. The concentration in the former varies depending on the process, ranging anywhere from 20% to 30% in iron and steel facilities to 98–99% in ammonia plants (Bains et al., 2017). The concentration of CO_2 in the air is roughly 400 parts per million (ppm) by volume (circa 0.04%), which is 100–300 times more dilute than flue gases from gas- and coal-fired plants. For this reason, the process requires a higher surface area of the solvent to be in contact with the input stream, which in turn requires a different physical design and the use of fans. The energy requirement for powering the fans in DAC is considerably higher (~7–22%) compared to industrial CCS (3%). However, that power can be supplied from renewables (Bui et al., 2018); thus, locating DAC at sites with low-cost renewable supplies would help lower overall costs. Other factors contributing to the lower overall costs are unique contract designs that are specific to DAC and cheaper materials (Kiani, Jiang and Feron, 2020)

2.3 CO_2 capture in the power sector (fossil fuel and biomass)

Despite the significant and growing deployment of renewables, fossil fuel-based power plants still dominate electricity generation and new plants are still being commissioned. In 2021, electricity generation from fossil fuels is projected to be responsible for 13 $GtCO_2$ of emissions (IRENA, 2021a).

Capturing carbon from power plants to reduce emissions is technically feasible, but economically challenging. There is currently only one power plant with CCS operating globally, it uses the post-combustion approach, but some power plants at different stages of development indicating the use of pre-combustion or oxy-combustion. In addition, several front-end engineering design (FEED) studies have explored the use of pre-combustion and oxy-fuel technology (IEAGHG, 2019b).

FIGURE 23: Non-exhaustive list of CCS/CCU projects in fossil fuel power generation at different stages of operation

● Pilot and demonstration ● Commercial

			Status							
Facility	Location	Capacity Mtpa/CO_2	In evaluation	Early development	Advanced development	Completed	Operating	Cancelled	On hold	Suspended
Aberthaw	UK	0.02				Pilot and demonstration				
AEP Mountaineer	USA	0.1				Pilot and demonstration				
Belchatow CCS Project	PL	0.1-1.8						Pilot and demonstration		
Boundary Dam CCS	CA	1					Commercial			
Brindisi	IT	0.008				Pilot and demonstration				
Cal Capture	USA	1.4			Commercial					
Caledonia Clean Energy Project	UK	3.8		Commercial						
China Resources Power (Haifeng) Integrated CCS	CN	1	Pilot and demonstration							
Citronelle	USA	0.25					Pilot and demonstration			
Compostilla	ES	1				Pilot and demonstration				
Coolimba Oxy-fuel Project	AU	2.9						Commercial		
Don Valley Power Project	UK	1.5							Commercial	
Dongguan Taiyangzhou Plant	CN	1		Pilot and demonstration						
Great River Energy	USA	-					Pilot and demonstration			
HECA: Hydrogen Energy California Project	USA	2.7						Pilot and demonstration		
Huaneng GreenGen IGCC Project (Phase 3)	CN	2		Commercial						
Kemper County Energy Facility	USA	3						Commercial		
Korea CCS-1	KR	1		Commercial						
Korea CCS-2	KR	1		Commercial						
Medicine Bow	USA	2.5						Commercial		
Mongstad	NO	1-2.5						Pilot and demonstration		
Northeastern Station	USA	1.5							Commercial	
OGCI Clean Gas Project	UK	5								
Osaki CoolGen-Phase II	JP	-			Pilot and demonstration					
Osaki CoolGen-Phase III	JP	-		Pilot and demonstration						
Peterhead CCS Project	UK	1						Commercial		
Petra Nova	USA	1.4								Commercial
Plant Barry	USA	0.185				Pilot and demonstration				
Polk Station	USA	0.3								
Puertollano	ES	0.04				Pilot and demonstration				
ROAD: Rotterdam Opslag en Afvang Demonstratieproject	NL	1.1							Pilot and demonstration	
RWE Goldenbergwerk	DE	2.3							Commercial	
Schwarze Pumpe	DE	0.08								
Shand CCS	CA	2	Pilot and demonstration							
Shanxi	CN	2		Pilot and demonstration						
Shidongkou	CN	0.1					Pilot and demonstration			
Sinopec Shengli Powerplant CCS	CN	1		Commercial						
Texas Clean Energy Project	USA	2.4						Commercial		
White Rose CCS Project	UK	2						Pilot and demonstration		

AU - Australia, CA - Canada, CN - China, DE - Germany, ES - Spain, IT - Italy, JP - Japan, KR - Republic of Korea, NL - Netherlands, NO - Norway, PL - Poland, UK - United Kingdom, USA - United States.
Source: Based on EC (2021); Global CCS Institute (2020a); MIT (2016).

The first pilot project was carried out between 2008 and 2013 on a coal power plant in Germany and captured 0.08 Mtpa CO_2. Since then, an additional 24 small-scale pilot and demonstration projects have been planned, of which nine have been completed, six are at different stages of advancement, three are in operation and seven have been put on hold or cancelled.

Only one large-scale project is currently in operation (120 MW) in a global fleet of coal plants that totals around 2 125 GW. The Boundary Dam plant in Canada is a 120 MW coal-powered unit that, since 2014, has been operating with a post-combustion process using the most common solvent, monoethanolamine (MEA), to capture 90% of CO_2 emissions (around 1 Mtpa CO_2). In 2019, after two years of operation, the 1.4 Mtpa CO_2 Petra Nova project capturing CO_2 emissions from a coal-powered plant in Texas, in the United States, was suspended. The suspension was due to a mix of economics and underperformance. Seven other commercial plants have been planned but cancelled or put on hold before becoming operational. A further seven commercial plants are at various stages of development.

Figure 23 provides an overview of identified commercial, pilot and demonstration projects in coal or gas power generation. Plans for such plants are constantly evolving and often the status is commercially sensitive and not publicly available. This list is not definitive, therefore, but is indicative of the current status and near-term potential.

Leading technologies

The two predominant approaches to capture CO_2 emissions in the power sector that have been explored in pilot projects and demonstrations are:

Amine scrubbing post-combustion capture: post-combustion with the most common solvent, MEA, is the most mature technology for capturing carbon from power generation. While the MEA solvent process is a mature and fairly widely used method, several other solvents are emerging that perform better by reducing the temperatures needed for regeneration. Using a Piperazine/amino-methyl-propanol (Pz/AMP) blend, CO_2 avoidance costs can be reduced by 22% for coal and 15% for gas-fired power plants compared to MEA. This difference arises due to marginally higher CAPEX, OPEX and fuel costs for MEA solvents (IEAGHG, 2019b).

Calcium looping with oxy-fuel combustion: Calcium looping uses calcium oxide (CaO) as a regenerative solvent. Calcium looping is used in conjunction with oxy-fuel combustion because high temperatures are required to regenerate the sorbent. The higher temperatures reduce the energy penalty by 3% compared to MEA capture and increase the power generation, as more steam is produced. However, it comes at a higher levelised cost of electricity (LCOE), at USD 140/MWh, and avoided cost of CO_2 capture (USD 105/tCO_2) compared to MEA or Pz/AMP solvents (Mantripragada and Rubin, 2014).

Energy penalty

One impact of carbon capture is the additional energy requirement of the capture process, which reduces the plant's net energy output. The energy penalty varies for different plants and capture processes, reducing the net efficiency of the plant by 6–13% (Cebrucean, Cebrucean and Ionel, 2014). More recent analysis suggests that CCS reduces the efficiency of a combined cycle gas turbine (CCGT) plant by between 7 and 11 percentage points (implying an increased fuel burn of 17–22% relative to the plant without CCS) and between 9 and 10 percentage points for super-critical coal plants (an increased fuel burn of 27–33% [IEA/NEA, 2020]).

Costs

At current costs, natural gas- or coal-fired power plants with CCS cannot compete with renewable power. The LCOE from gas and coal-fired plants with a 90% capture rate is higher than the equivalent plant without CCS, given the higher capital costs, the energy penalty of CCS and other operating costs (personnel, parts and consumables). For a CCGT, the LCOE of a plant with CCS (including CO_2 transport and storage) is potentially 70–140% higher than that without, without accounting for residual CO_2 emissions and upstream methane emissions from fuel production and transport (Figure 24).[13]

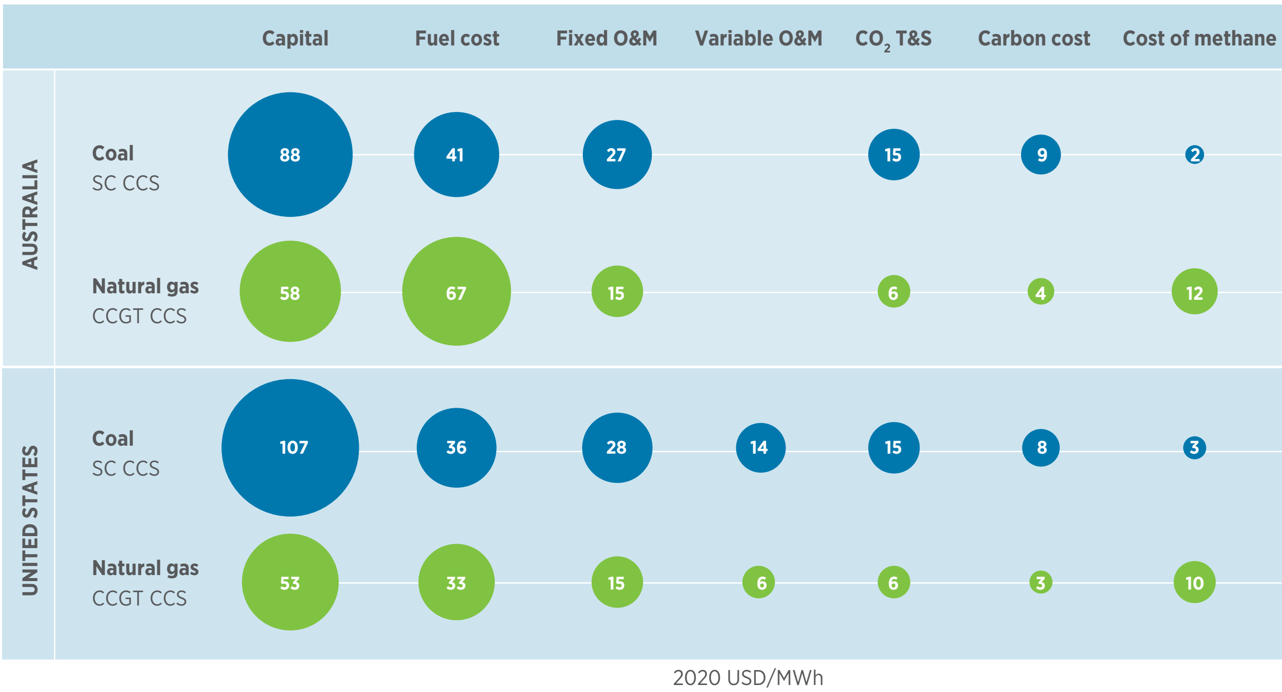
In the United States, power purchase agreements (PPAs) and auction results for utility-scale solar PV and onshore wind that will come online in 2021 suggest average costs of USD 31/MWh and USD 37/MWh, respectively. Coal with CCS would be around 5–6 times more expensive in 2025 (assuming, unrealistically, no further cost reductions for solar and wind by then), while a CCGT with CCS would be 3.1–3.7 times more expensive. For a CCGT in 2025, this represents a premium of USD 82–88/MWh over new solar and wind to be commissioned in the United States in 2021.

Future cost reductions in CCS for power production are likely but the lack of momentum to date makes the near- and medium-term CCS cost reduction potential uncertain. Given that renewable power production continues to be added at record capacity and costs continue to rapidly fall, the gap between CCS and renewable power is unlikely to narrow quickly.

A further challenge for fossil fuel power production with CCS is that it is unlikely to be deployed before significant shares of renewables are deployed as part of a net-zero pathway. This will mean very few plants will achieve high load factors, as they will have to flex to accommodate solar and wind generation, further impacting their economics.

A potential benefit of CCS in power is its dispatchability; utility-scale solar PV and storage is currently being contracted in the United States for a total cost of USD 29–44/MWh, for a storage duration of up to four hours (IRENA, 2021b). For comparison, the estimated capital cost of a CCGT plant with CCS at a capacity factor of 50% is USD 53/MWh, exceeding the total LCOE of solar plus storage by at least 20%. That cost gap implies that even as a low-carbon dispatchable technology, CCS power plants will struggle to compete with utility-scale solar PV with storage.

FIGURE 24: LCOE of CCGT and supercritical coal-fired power plants for commissioning in 2025 in Australia and the United States



Sources: IRENA analysis based on Australian Government (2021); IEA/NEA (2020); NETL (2019); US.EPA (n.d.).

13 If net-zero is the goal, these remaining emissions cannot be ignored and must be factored into the economics of CCS in the power sector.

Integration of biomass with CO_2 capture in the power sector

BECCS captures and stores the released CO_2, resulting in 'negative' emissions. It is a combination of biomass conversion into heat, electricity or fuel, coupled with the CCS technology. While many countries have committed to phase out the use of fossil fuels, the process is lengthy and depends on many factors. The advantage of BECCS is its potential to be retrofitted into existing fossil fuel power plants via biomass co-firing. As such, it could offer a transition pathway to the full use of biomass coupled with CCS. However, the integration of biomass in power plants represents a challenge itself, with limited learning experience. A majority of plants address either the use of biomass in processes or focus on CCS, but rarely focus on both. Understanding the routes and challenges associated with the integration of biomass to be later coupled with CCS can represent a viable start.

The co-firing of biomass in coal-fired power generation with CCS

The co-firing of biomass in coal-fired power plants is a cost-effective option for partially reducing emissions and can be retrofitted quickly, particularly in the short term. Direct co-firing is the most common and the least costly option. It is straightforward but depends on the biomass used and its fuel properties. The use of biomass tends to be limited to just 10–20% of total energy use due to the presence of fly ash from coal and highly alkaline ash from biomass that may form agglomerates in the boiler (IEAGHG, 2019a). An alternative approach is indirect co-firing, wherein biomass feedstock is first gasified to produce syngas, and only then co-fired. It offers fuel flexibility but it is currently less used and researched.

Biomass direct co-firing with coal reduces emissions, as it reduces fossil fuel consumption. For example, in the United States and the European Union, roughly 76% of total emissions are reduced compared to coal-fired power plants with 20% biomass co-firing (Beagle and Belmont, 2019). Moreover, co-firing with biomass requires little or no additional investment and maintenance activities. One study suggests that 10% biomass co-firing in an ultra-super critical (USC) coal-fired plant with a 90% capture rate is the most economical option to achieve zero emissions (IEAGHG, 2019a). Biomass gasification can increase efficiency but comes with technological barriers such as tar reduction.

TABLE 3: Overview of economics and emissions of coal-fired power generation via different methods

	Ultra-super critical PC with 10% biomass co-firing with CCS (post-combustion using MEA)
Capture rate	90%
Cost of CO_2 avoided (USD/tCO_2)[14]	62.4
Emissions intensity (tCO_2/MWh)	0
Energy Consumption (MWh/CO_2)	0.337
LCOE (USD/MWh)	98
CAPEX USD/kW)	3 028

Source: Based on IEAGHG (2019a).

There is a possibility to substitute coal with 100% biomass in pulverised coal boilers. This approach requires a high-quality pre-treated biomass source. High-grade biomass allows the furnace to retain the same heat absorption properties as would have been in the case of coal. In addition, lower sulphur and chlorine levels in the biomass reduce the need for acid gas clean-up and the risk of high-temperature corrosion of boilers. The process involves milling biomass into particular sizes for suspension firing, followed by direct injection into the

14 Consists of costs for capturing the carbon and does not include transport or storage costs.

boiler system. There are, however, several concerns about the formation of slag on heaters, burners and other refractory surfaces, as well as at the boiler convective pass. This would reduce the performance and accessibility of combustion applications. Therefore, it is imperative to know the ash properties of the biomass by conducting a full-ash analysis to select the right source (IEAGHG, 2019a). To optimise operation, site testing and regular monitoring of slag formation in the first months/year of operation are also required. But experience is limited, as the power plants are either not coupled with the CCS or have undergone limited screenings and techno-economic assessments (Emenike et al., 2020; Bhave et al., 2017).

There are two examples of the conversion of coal-fired power boilers to 100% biomass coupled with CCS: the Drax power plant (UK), with the CCS unit expected to be operational by 2027 (Drax, 2021); and the demonstration project at the Mikawa power plant in Japan, launched in 2021 (Toshiba-energy, 2021). The remaining examples of conversion of coal-fired power boilers into 100% biomass are: Avedore power plant, Denmark; Atikokan power plant, Canada; and the combined power and heat plant in Hässelby, Sweden; but all without CCS.

Integration of biomass in natural gas power generation with CCS

Another opportunity to mitigate CO_2 emissions in the power sector is by integrating gasified biomass (indirect co-firing) into a natural gas combined cycle power plant (NGCC). The use of biomass is limited to 40% (Agbor et al., 2016). Several technologies (atmospheric air-blown, pressurised oxygen-blown, and atmospheric indirectly heated gasification) can be used for biomass gasification and their selection predominantly depends on the level of biomass co-firing. But in terms of emissions reduction and plant efficiency, the selection of technology does not play a significant role. Co-firing may require some modification to the gas turbines, such as replacing the combustion chamber if lower heating biogas is used. Due to indirect co-firing, the post-combustion capture is the most appropriate.

An increase in co-firing levels increases the concentration of CO_2 in flue gas and the capture rate increases from 80% without biomass to 90% with biomass (Khorshidi et al., 2016). This, in turn, reduces the energy penalty for post-combustion capture, despite the clean-up of syngas produced. An increase in co-firing levels also requires larger capture units to capture a higher amount of CO_2, which comes with higher CAPEX and OPEX, but due to the higher concentration of CO_2 in the flue gas, the avoided costs[15] for capturing carbon reduce from USD 69/tonne CO_2 (at 5% co-firing level) to USD 46/tonne CO_2 (at 40% co-firing level) (Khorshidia et al., 2016).

Co-firing in NGCC plants is currently rarely used and is still in a development stage. An example of a commercial natural gas/biomass co-firing plant is in Finland. This plant uses sawdust, straws, wood wastes and other waste-derived fuels, but does not have a capture technology.

Still, more research is needed into the overall impact on avoidance costs of biomass gasification with NGCC plants and its integration with CO_2 capture technology. Currently, these are mostly techno-economic assessments and feasibility studies, but demonstration and first-of-a-kind projects are missing.

15 Interpreted as avoided costs (with zero Renewable Energy Certificate) from the Breakeven Carbon Price metric in Khorshidia et al., 2016 (which is a mix of avoided cost of capture and REC). Khorshidia et al., define avoided costs of CO_2 as breakeven carbon price applied to make technology cost-competitive with no capture plant.

2.4 CO_2 capture in industrial processes

A significant proportion of CO_2 emissions come from industrial processes. In 2017, 7.8 Gt of CO_2, representing 20% of all emissions, was attributed to cement, iron and steel, and chemical and petrochemical production. Under current policies, this proportion will increase to 22% by 2050, notably with increases from the chemical and petrochemical sectors.

Given that over 60% of process-related emissions from cement production and over 5% of process-related emissions from the blast furnace–basic oxygen furnace (BF-BOF) method of steel production come from calcination processes, these sectors have been a focus of CCS studies and demonstration projects over the last decade, predominantly in Europe.

As physical properties, composition and gas volume flows all vary in each industrial process, the suitability of different capture technologies, including their impacts on the production process and final product quality, associated energy penalties, "retrofit-ability" and costs, are still being investigated.

Natural gas processing

Drilling, extraction and transportation of natural gas through pipelines globally emits 150 Mtpa of high purity CO_2 (Global CCS Institute, 2020a). This CO_2 requires only dehydration before it can be stored. Capturing carbon from processing natural gas is one of the oldest applications of carbon capture technologies. The first commercial plant was installed in 1972, capturing 1.3 Mtpa of CO_2 and since then, 18 other commercial projects have been installed, with the largest capacities in the United States (with the largest capturing 7 Mtpa of CO_2). Eleven currently operating plants have a combined capture capacity of 26.3 Mtpa CO_2 and, when finalised, five plants currently under construction will increase capture capacity to 34.2 Mtpa CO_2. There have also been 10 pilot or demonstration projects – six completed, three ongoing and one in development. Plans for such plants are constantly evolving and often their status is commercially sensitive and therefore not publicly available. This list (Figure 25) is not definitive, therefore, but is indicative of the current status and near-term potential.

Typically, pre-combustion capture is used with costs of USD 20–25/tCO_2 avoided. However, future natural gas demand may require extraction from wells with high partial pressures. For this, pressure swing absorption might be suitable, which will increase costs to USD 31/t CO_2 avoided (IEAGHG, 2017b).

Cement production

Cement is a critical building material. Its production grew globally from 3.3 Gt in 2010 to 4.1 Gt in 2019, with China representing 54% of global cement production. In 2017, cement and lime production accounted for 2.5 Gt of energy- and process-related CO_2 emissions, representing 7% of total global emissions (IRENA, 2020).

The most common cement produced globally is Portland cement, which releases, on average, 866 kg of CO_2 per tonne of cement (IRENA, 2020). Calcination of limestone to produce clinker represents 60–65% of direct CO_2 emissions; the remaining 35–40% of CO_2 emissions come from fuel combustion used to heat the kiln (Hills, Sceats and Fennell, 2019). These emissions are difficult to fully eliminate, as there are yet no clinker or limestone substitutes, and thus CCS or CDR technologies (BECCS or DACCS) will have a crucial role.

From the technology perspective, the pre-combustion approach is the least effective. It would eliminate only one-third of fuel emissions, as two-thirds of CO_2 emissions originate from the calcination of limestone and are not captured in the pre-combustion process. As cement plants have a lifetime ranging from 30 to 50 years, the ease of retrofit is also relevant. Pre-combustion can be applied only to new plants in a cost-effective way, while post- and oxy-combustion are suitable for the retrofitting of existing cement plants. Post-combustion and oxy-combustion are therefore more effective.

FIGURE 25: Non-exhaustive list of CCS/CCU projects from natural gas processing in different stages of operation

- Pilot and demonstration
- Commercial

Facility	Location	Capacity Mtpa/CO_2	Status: In evaluation	Status: Early development	Status: Completed	Status: Operating	Status: Cancelled	Status: On hold	Status: Suspended
Abu Dhabi CCS (Phase 2)	UAE	1.9 - 2.3	● Commercial						
Acorn CCS	UK	0.2		● Commercial					
Bell Creek	USA	1				● Commercial			
Century Plant	US	5 – 8.4				● Commercial			
Fort Nelson	CA	2.2					● Commercial		
Gordon Carbon Dioxide Injection Project	USA	3.4 - 4.0				● Commercial			
H21 North of England	UK	3		● Commercial					
In Salah	DZ	0							● Commercial
Ivanic/Zutica	HR	5.4			● Pilot and demonstration				
K12-B	NL	0.08			● Pilot and demonstration				
Ketzin	DE	0.1			● Pilot and demonstration				
La Barge	USA	1		● Commercial					
Lost Cabin Gas Plant	USA	0.9				● Commercial			
NET Power	USA	-				● Pilot and demonstration			
Northern Reef	USA	0.365				● Pilot and demonstration			
Otway - stage 1	AU	0.065			● Pilot and demonstration				
Petrobras Lula	BR	0.7				● Commercial			
PetroChina Jilin Oil Field EOR Project (Phase 2)	CN	0.6				● Commercial			
Riley Ridge Gas Plant	USA	2.5						● Commercial	
Shute Creek Gas Processing Facility	USA	7				● Commercial			
Sleipner	NO	0.9				● Commercial			
Snohvit	NO	0.7				● Commercial			
Spectra Energy's Fort Nelson CCS Project	CA	2.2				● Pilot and demonstration			
Uthmaniyah	SA	0.8				● Commercial			
Val Verde	USA	1.3				● Commercial			
Zama	CA	0.026			● Pilot and demonstration				

AU - Australia, BR - Brazil, CA - Canada, CN - China, DE - Germany, HR - Croatia, NL - Netherlands, NO - Norway, SA - Saudi Arabia, UAE - United Arab Emirates, UK - United Kingdom, USA - United States.
Sources: Based on Global CCS Institute (2020a); MIT (2016).

Post-combustion technologies are adapted from the power sector and offer the most developed approaches. Capture technologies differ from each other in their TRLs, capture rate, avoided CO_2, energy penalty, complexity to retrofit, required major changes to the cement process, impact on cement quality, and CAPEX and OPEX.

Post-combustion

Amine scrubbing

While amine scrubbing is the most mature post-combustion technology adapted from the power sector, its scale-up in the cement sector remains an issue. In amine scrubbing, the amine liquid solvent is used to scrub CO_2 from a flue gas, which in the case of cement contains impurities. Amine solvents are sensitive to dust and contamination with other gases. To avoid solvent degradation, the flue gas requires pre-treatment, which impacts its energy footprint, CAPEX and OPEX. After clean-up, the amine solution is pumped into another reactor – a desorber – by steam. This process requires thermal energy of 3–4 GJ/t CO_2 (Bui et al., 2018), and an additional combined heat and power system may be necessary, as the low-grade heat available at the cement plant is insufficient. The process also requires a significant power supply for fans and pumps in the absorption process. The amine scrubbing offers several benefits, including no significant changes to the original plant and processes, only minimal impacts on the energy management and start-up and shut-down procedures, and no observed changes to cement quality. Retrofitting of the existing plant is possible during annual shutdown periods but requires considerable space, which may be a constraint.

There is limited operational experience in the cement sector; however, there are several pilot and demonstration projects as well as several announcements to build large-scale commercial CCS facilities.

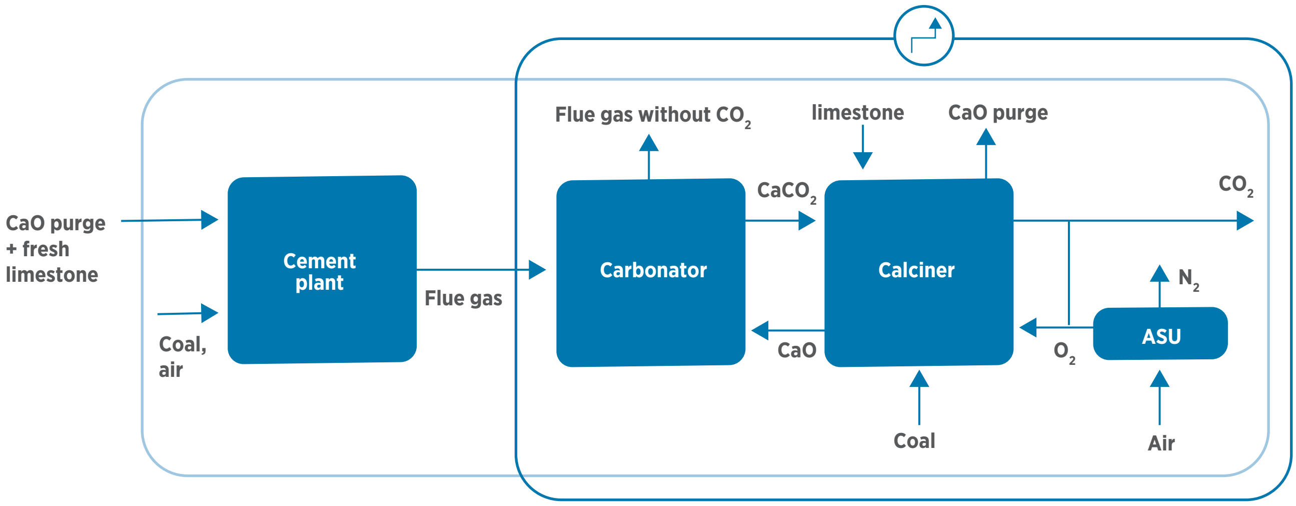
The European CEMCAP[16] project gathered major cement producers and assessed several capture technologies for retrofitting existing cement plants from a technical and economical perspective. Following a successful demonstration project at Norcem in Norway (capturing 370 tonnes of CO_2 over 2 700 hours with a capture rate of 90%), in 2020 Norway's Longship project announced a large-scale commercial CCS facility at Norcem to be operational in 2023, with the aim to capture 0.4 Mtpa of CO_2 (AkerSolutions, 2019). Captured CO_2 will be liquefied and first shipped and then transported by pipeline under the North Sea via the Northern Lights transport and storage project (Government of Norway, 2020). Since 2018, Anhui Conch's CCU facility at its cement plant in China has been capturing 0.05 Mtpa of CO_2 and selling the captured CO_2 to industrial consumers to cover expenses (CemNet, 2019). In 2019, India's Dalmia Cement and UK-based Carbon Clean Solutions committed to building a large-scale CCU plant at one of Dalmia's cement plants in India. The plant will have the capacity to capture 0.5 Mtpa of CO_2 and Dalmia aims to sell captured CO_2 for chemical production and other non-specified uses. There is no further information on the data or budget, however (González Plaza, Martínez and Rubiera, 2020).

Calcium looping

In a carbonator (Figure 26), CO_2 reacts with calcium oxide in the flue gas to form solid calcium carbonate. CO_2-lean flue gas is emitted, while solid calcium carbonate is passed to the calciner, where it decomposes back to CO_2 and calcium oxide. The result is pure CO_2. While the reaction of CO_2 with calcium oxide is exothermic and allows the heat from the carbonator to be used in a steam cycle or produce enough electricity to power other units in the cement plants, the calcination process is highly endothermic and drives the energy penalty up. Calcium looping comes with benefits: there are no major changes to the original plant and processes but retrofitting with the replacement of the precalciner with dual-fluidised bed systems may cause a prolonged shutdown. Space may be a constraint as well. There are no observed changes to the cement quality at the laboratory scale but, in a real setting, minimal changes are possible.

16 www.sintef.no/cemcap/

FIGURE 26: Cement production and components



Source: (IEAGHG, 2013b)

There is a synergy between cement production and calcium looping capture, as the process uses cement's main feedstock – calcium oxide (CaO) – as its main sorbent, which is available in industrial quantities and is environmentally benign.

The EU-funded CEMCAP project (at the Norcem plant, Norway) assessed the calcium looping from a technical and economic perspective, and the follow-up CLEANKER project aims to demonstrate the technology in Italy.

Oxyfuel combustion

Oxygen is mixed with recycled CO_2 and then fed into the kiln and precalciner. In oxy-combustion, the fuel is burned using nearly pure oxygen. The produced flue gas after the clean-up contains water and CO_2, which makes it easy to be separated by filtering O_2 from the air before burning the fuel by low-temperature dehydration and desulphurisation.

Full oxy-combustion has significant impacts on cement production, with retrofitting entailing an estimated six-month shut-down. It requires new additional equipment and related permits, including new preheaters and precalciners, specific oxyfuel clinker coolers, an exhaust gas recirculation system air separation unit, and a CO_2 purification unit or rotary kiln burner. The majority of new equipment needs to be installed in the vicinity of the kiln, which creates space issues (but lower constraints than amine scrubbing). It incurs a major energy penalty, with additional power demand up to 120 kWh to run an air separation unit.

Operational experience is limited to the power sector. Since 2007, the European Cement Research Academy (ECRA) has carried out research on oxy-combustion and in 2018 launched two demonstration projects at an industrial scale in two European cement plants at HeidelbergCement Italy and LafargeHolcim in Austria. The aim is to reach TRL 7–8.

Direct separation

A novel approach to directly separate CO_2 is being explored by the EU-funded project LEILAC (Low Emissions Intensity Lime and Cement). In the direct separation process, CO_2 is removed from limestone during the heating process in a separate steel reactor, which enables pure CO_2 to be captured as the furnace gases are kept separate (Calix, 2020). LEILAC successfully demonstrated that direct separation could capture 95% of process emissions and is now entering its second phase with LEILAC 2 building a plant in HeidelbergCement to demonstrate its efficiency. This process, however, would not reduce fuel emissions, as only process emissions can be captured (Hills, Sceats and Fennell, 2019).

Figure 27 provides an overview of CCS and CCU post- and oxy-combustion projects in the cement sector. Only one project in China is currently operational. It is a small-scale project capturing 0.05 Mtpa of CO_2, which is then destined for utilisation. The large-scale Dalmia CCU Plant is in early development and aims to capture 0.5 Mtpa CO_2. There are several pilot and demonstration projects – three completed and six at different stages of development. Plans for such plants are constantly evolving and often the status is commercially sensitive, so information is not publicly available. This list is not definitive, therefore, but is indicative of the current status and near-term potential.

FIGURE 27: Non-exhaustive list of CCS/CCU projects in cement sector at different stages of operation

🔵 Pilot and demonstration
🟠 Commercial
⚫ Feasibility Study
🔴 Laboratory

Facility	Location	Capacity Mtpa/CO_2	Status					
			In evaluation	Planning	Early development	Advanced development	Operating	Completed
Anhui Conch's CCU facility	CN	0.05					🟠	
CEMCAP	EU	0						🔴
CI4C - Oxyfuel Research Corporation	DE	1			🔵			
CLEANKER	IT	-					🔵	
CO_2 capture pilot, Brevik	NO	-						🔵
Co2MENT	CA	0.0004					🟠	
	USA	0.7 - 2				🔵		
Dalmia Cement	IN	0.5			🟠			
ECRA - Colleferro plant	IT	-		🔵				
ECRA - Retznei plant	AT	-		🔵				
ITRI Pilot	CT	-						🔵
Lehigh CCS Feasibility Study	CA	0.6			⚫			
LEILAC	BE	0.088						🔵
LEILAC 2	DE	0.1			🔵			
Norway Full Chain CCS - Brevik, Longship	NO	0.8				🟠		
WestKuste 100	DE	0.72	🔵					

AT - Austria, BE - Belgium, CA - Canada, CN - China, CT - Chinese Taipei, DE - Germany, EU - European Union, IN - India, IT - Italy, NO - Norway, USA - United States.
Sources: Based on EC (2021); Global CCS Institute (2020a); MIT (2016).

Costs

The avoided costs of capture depend on factors including the concentration of CO_2 from flue gas, type of capture, properties of capturing solvent, sorbents and membrane, among others. The avoided CO_2 costs for a plant with post-combustion capture (90% capture rate) using MEA solvent is in the range of USD 63–94/tCO_2; using calcium looping is cheaper and costs of avoided CO_2 are USD 20–70 (Table 4). Full oxy-combustion captures over 90% of CO_2 with avoided costs of USD 44–46/tCO_2, while partial oxy-combustion captures around 65% of CO_2 with avoided costs of USD 55–60/tCO_2.

TABLE 4: Selection of post- and oxy-combustion technologies to capture CO_2 in cement plants

	Post-combustion		Oxy-combustion
	Amine scrubbing, using MEA	**Calcium looping**	**Full**
Capture rate	>90%	>90%	>90%
Cost of CO_2 avoided (USD/t) [17]	63–94	58–84	44–46
Energy penalty	High[18]	High but lower than amine scrubbing	High
Complexity for retrofit (low, medium, high)	**Low** Minimal changes, but extensive flue gas cleaning	**Low–medium** Precalciner replaced with dual-fluidised bed; capture plant can be placed anywhere.	**High** Increased design and maintenance complexity; plant's operation changes with new preheaters and precalciners.
Cement quality	No change	No to limited changes	No changes
CAPEX (USD)	**Retrofit** 24–34/t cement; **New plant** 43–51/t cement	48–52/t clinker	**Retrofit** 10/t cement; **New plant** 28/t cement
Cost of clinker (USD/t)	119–124	119–124	105
TRL	6-8	3–6	4
Commercial availability	2025–2035	2025–2030	2040–2045

Sources: Based on De Lena et al. (2019); Hills et al. (2016); Hills, Sceats and Fennell (2019); IEAGHG (2013b); Volsund et al. (2018).

Iron and steel production

The iron and steel sector is a large energy user and CO_2 emitter. In 2017, the sector accounted for 32 EJ of total global final energy use and emitted 3.1 Gt of energy- and process-related CO_2 emissions, which accounted for 8% of global CO_2 emissions (IRENA, 2020). In 2018, the sector produced 1 810 Mt of steel.

Steel is produced in two ways: either in integrated steel mills using the blast furnace–basic oxygen furnace route (BF-BOF) or in foundries with an electric arc furnace (EAF) using directly reduced iron (DRI), scrap metal and cast iron. Integrated steel mills represent over 70% of global steel production (Mousa et al., 2016) and are the largest sources of emissions, emitting 3.5 Mtpa of CO_2, compared to less than 200 ktpa of CO_2 emitted by mini-mills. An average steel plant emits 1.8 tCO_2 per kg of crude steel produced, out of which 1.7 tonnes comes from

17 Consists of costs for capturing the carbon and does not include transport or storage costs.
18 There is a lack of numerical data to quantify energy penalties for different capture routes in cement production.

coke or coal while 0.1 tonnes is from limestone (Bui et al., 2018). There are two options to decarbonise iron and steel production: to adapt DRI to use renewable hydrogen as the reducing agent and energy source; or to apply capture technology to BF–BOF. The current research on capture in iron and steel focuses heavily on applying capture to the blast furnace, primarily because it emits almost 70% of the direct CO_2 emissions from the entire steel production process, making it highly suitable for capturing CO_2.

Different technologies can capture CO_2 from a steel production process. CO_2 results from using coke to draw oxygen out of the iron ore. However, the suitability of any technology depends on whether it is retrofitted to an existing plant or added to a new plant. For instance, for retrofitting, a post-combustion method is suitable, as it does not involve any significant changes to the production process. However, for a new plant, a top gas oxyfuel variant of post-combustion is more suitable because of its low cost and higher capture rates. In both cases, several methods can be used for the CO_2 capture: absorption (physical or chemical), adsorption, or membrane separation.

Amine scrubbing post-combustion capture

As in the power and cement industry, capturing carbon using amine solvents is the most mature technology and is used also in the iron and steel industry. The solvent captures carbon from the flue gas and is regenerated at a high temperature and low pressure. The most common solvents are monoethanolamine (MEA) or methyldiethanolamine (MDEA) due to higher capture rates and selectivity. However, traditional amine solvents corrode equipment, degrade solvents and require high energy for regeneration. Newer pilots and demonstration projects are testing advanced amino-alcohol with fewer limitations, such as lower energy for regeneration. Japan's Nippon steel plant tested a new solvent under the COURSE50 program and reported an energy reduction of 2–3 GJ/CO_2 for regenerating the solvent (McQueen et al., 2019).

Oxy-fuel top gas recycled blast furnace (TGR-BF)

The TGR-BF developed by the ULCOS (Ultra-Low Carbon Dioxide Steelmaking) project in Sweden uses a pure stream of oxygen instead of air, resulting in the efficient combustion of the coal. This increases the concentration of CO_2 in the flue gas resulting in a lower avoided cost of CO_2. Then the CO and H_2-rich stream is reinjected into the blast furnace. These gases act as reducing agents, thus lowering the need for coke and coal. The pilot, on capturing carbon on the TGR-BF using adsorption capture technologies such as Pressure Swing Absorption and Vacuum Swing Adsorption, reports capturing 65% of emissions.

The application of capturing CO_2 is currently limited to only one commercial plant. Since 2016, the Abu Dhabi CCS Phase 1 has captured 0.8 Mtpa of CO_2. Five pilot and demonstration projects apply carbon capture in steelmaking processes such as blast furnace route, DRI-EAF and smelting reduction. A few prominent examples of these pilot-scale initiatives are ULCOS's TGR-BF with CCS, POSCO's CCS with vacuum swing adsorption, and COURSE 50's CCS from BF using amine absorption. The scale of the production and capture varies from project to project. For instance, ULCOS's TGR-BF project has a capacity to capture 1.4 ktpa, while its German counterpart can produce 700 ktpa. In South Korea, POSCO's CCS has a capture capacity of 0.18 ktpa CO_2 (Bui et al., 2018).

Figure 28 provides an overview of CCS and CCU projects in the iron and steel sector, showing that, in addition to one commercial project in operation, there are eight pilot and demonstration projects – five are operating in Japan, Sweden, France and Germany, while two other European projects are in different stages of development and one has been cancelled. Plans for such plants are constantly evolving and often the status is commercially sensitive so information is not publicly available. This list is not definitive, therefore, but is indicative of the current status and near-term potential.

FIGURE 28: List of CCS and CCU projects in the iron and steel sector at different stages of development

- ● Pilot and demonstration
- ● Commercial
- ● Feasibility Study

Facility	Location	Capacity $Mtpa/CO_2$	Status					
			Early development	Advanced development	Under construction	Operating	Completed	Cancelled
Abu Dhabi CCS (Phase 1)	UAE	0.8				● (Commercial)		
ArcelorMittal Steelanol	BE	1			● (Pilot and demonstration)			
BHP Iron and Steel Sector CCS Project	CN	-					● (Feasibility Study)	
C6 Resources CCS Project United States	USA	-						● (Pilot and demonstration)
COURSE 50	JP	0.01				● (Pilot and demonstration)		
DMX demonstration in Dunkirk	FR	0.5		● (Pilot and demonstration)				
SEWGS-STEPWISE	SE	0.005				● (Pilot and demonstration)		
ULCOS Florange	FR	0.5				● (Pilot and demonstration)		
ULCOS HIsarna CCS	DE	0.8	● (Pilot and demonstration)					
White Biotech CCS	CT	-				● (Pilot and demonstration)		

BE-Belgium, CN-China, CT-Chinese Taipei, DE-Germany, FR-France, JP-Japan, SE-Sweden, UAE-United Arab Emirates, USA-United States.
Sources: Based on EC (2021); Global CCS Institute (2020a); MIT (2016).

Costs

The avoided costs of capture depend on the concentration of CO_2 from flue gas, type of capture, properties of capturing solvent, sorbent and membrane, among others. For instance, the avoided costs of CO_2 capture for a plant with a retrofitted post-combustion capture (90% capture rate) using MEA solvent is in the range of USD 80-160/tCO_2 (Table 5). The post-combustion capture using DMX™ solvent captures 99% carbon with an avoided cost of USD 32–48/tCO_2. The pilot DMX™ process will be installed at the ArcelorMittal steelworks site in Dunkerque, France to capture 0.004 Mtpa CO_2. The facility will start operation in 2021.

TABLE 5: Selection of post- and oxy-combustion technologies to capture CO_2 in iron and steel plants

	Post-combustion with absorption using MEA or MDEA Solvents	Oxy fuel top gas recycled BF with Pz/MDEA solvent[19]
Capture rate	>90%	47%[20] From BF it captures > 90%
Cost of CO_2 avoided (USD/ t CO_2)[21]	80–160	57
Energy penalty	**High** because of high temperature used for regeneration of solvent	**Low** because recycled flue gas is used as an input
Complexity for retrofit	**Low** Mature end of pipe technology but expensive flue gas clean-up required before capture.	**High** The plant needs to be equipped with an air separation unit that can produce the oxygen to fuel the BF.
Changes to ironmaking process	No changes	Changes to coke and sinter production to accommodate for reduced demand
Product quality	No changes	No changes
CAPEX for a new plant (USD)	494–634/t cs*	630/t HRC*
TRL	6–8	6
Commercial availability	2025–2035	2025–2035

Sources: Based on Bui et al. (2018); IEAGHG (2013a); Szczeniak et al. (2020); Toktarova et al. (2020).
*(cs) crude steel; (HRC) hot rolled coil.

Chemicals

In 2017, 1.3 Gt of petrochemicals and chemicals were produced, which emitted 1.1 Gt of CO_2 (IRENA, 2020). These emissions are expected to grow as the population increases, pushing up demand for commodities such as plastics. 28% of the total emissions from this sector can be abated through the use of CCS, CCU and BECCS (IRENA, 2021a). Furthermore, this sector represents low-cost opportunities for installing capture infrastructure, as the concentration of CO_2 in flue gas from these sources is high, especially for ammonia.

The capture and utilisation of CO_2 to produce these commodities do not necessarily imply that the emissions are reduced. This is due to lifecycle emissions from multiple end-uses. For instance, while captured CO_2 can be used for syngas production to produce ammonia, most ammonia is used to produce urea through which CO_2 is eventually released back into the atmosphere (IEAGHG, 2019c). Life-cycle emissions in the case of methanol also depend on its end-use and their current levels from methanol production are 0.3 Gtpa (IRENA and Methanol Institute, 2021). These considerations are particularly important in the case of plastics, as olefin production via the methanol-to-olefin (MTO) route is gaining traction, especially in China. Lifecycle emissions considerations for methanol are important, as plastic production through olefin production (intermediary) via methanol is increasing.

Several large-scale commercial, pilot and demonstration projects capturing CO_2 from the production of chemicals and petrochemicals have been in operation or are at different stages of development. Capturing CO_2 from the ammonia production process to produce urea is a common practice at integrated fertiliser plants. In addition to these, several large projects for ethanol and methanol production plants equipped with carbon capture are at different stages of development.

19 The BF considered in this case is different from ULCOS's TGRBF
20 Considers capture from the plant and not just from the blast furnace
21 Consists of costs for capturing the carbon and does not include transport or storage costs.

Five commercial plants are currently in operation and a further five are at different stages of development. In addition, two pilot and demonstration projects are completed, five are operating and two are at different stages of development. Plans for such plants are constantly evolving and often the status is commercially sensitive, so information is not publicly available. This list (Figure 29) is not definitive, therefore, but is indicative of the current status and near-term potential.

FIGURE 29: Non-exhaustive list of CCU and CCS plants in the petrochemicals and chemicals industry

- Pilot and demonstration
- Commercial

			Status						
Facility	Location	Capacity Mtpa/CO_2	In evaluation	Early development	Advanced development	Under construction	Operating	Completed	Cancelled
ACTL with Nutrien CO_2 Stream	CA	0.3 (Max 14.6)					Commercial		
Coffeyville Gasification	USA	1					Commercial		
Decatur	USA	0.33						Pilot and demonstration	
Enid fertiliser	USA	0.7					Commercial		
Farnsworth	USA	0.2					Pilot and demonstration		
Gulf Petrochemical Industries Company (GPIC) Capture Project	BH	0.16425					Commercial		
Jingbian	CN	0.05					Pilot and demonstration		
Karamay Dunhua Project	CN	0.1					Commercial		
Kurosaki Chemical Plant Capture Project	JP	0.1 - 0.12					Commercial		
Lake Charles Methanol	USA	4			Commercial				
Petronas Fertilisers Malaysia CCS Pilot	MY	0.07					Pilot and demonstration		
Project Interseqt (2 projects)	USA	0.63		Commercial					
Shenhua Ordos CTL Pilot Project	CN	0.1						Pilot and demonstration	
Shenhua Ordos CTL Project (Phase 2)	CN	0.1							Pilot and demonstration
Sinopec Qilu Petrochemical CCS project	CN	0.4	Pilot and demonstration						
Solvay Vishnu Capture Project	IN	0.077						Pilot and demonstration	
South West Hub	AU	2.5							Commercial
Wabash CO_2 Sequestration	USA	1.5 - 1.75			Commercial				
Yanchang CO_2-EOR project	CN	0.4				Commercial			
Yanchang Integrated CCS Demonstration project	CN	0.05					Pilot and demonstration		
Yulin Coal to Chemicals CCS	CN	1-2		Pilot and demonstration					

AU - Australia, BH - Bahrain, CA - Canada, CN - China, IN - India, JP - Japan, MY - Malaysia, USA - United States.
Sources: Based on EC (2021); Global CCS Institute (2020a); MIT (2016).

Costs

The costs of capturing carbon from ammonia and methanol production are lower than other industrial processes because of the highly concentrated nature of flue gases produced during production (Table 6). While the majority of CO_2 captured in ammonia production is used to produce urea, capturing carbon from methanol presents an opportunity for both CO_2 utilisation and carbon storage. Emissions from methanol production using fossil fuels lie in the range of 91–262 gCO_2eq/MJ (IRENA and Methanol Institute, 2021).

Ethylene is one of the most important olefins, used in the production of commercially useful chemicals (e.g. polymers like PVC and polyester) and commodities such as plastics. Ethylene can be produced in several ways, but steam cracking is the most widely used production method. The costs of capturing carbon from a steam furnace are higher than other industries (around USD 203/tCO_2 avoided) due to a low concentration of CO_2 in the flue gas (7–12%) (Table 7). The market entry of commercial ethylene-integrated CCS facilities is expected after 2030 (Szczeniak, Bauer and Kober, 2020). Considering the high costs and delayed deployment, methanol-to-olefins (MTO) is a much more viable production route.

TABLE 6: Overview of performance, cost and readiness levels for capturing carbon from ammonia and methanol production

	Ammonia		Methanol	
Feedstock	**Coal**	**Natural gas**	**Coal**	**Natural gas**
Capture rate	95%		95%	
CO_2 avoidance cost (USD/ tCO_2 avoided)[22]	15–40			
CAPEX (USD/t)	2 836	1 328	1 525	531
Cost of product (USD /t)	350–650	250–650	350–550	200–500
TRL	10		9	
Commercial availability	Already in commercial operation		2025	

Sources: Based on Szczeniak et al. (n.d.); IEA (2019).

Ethylene

TABLE 7: Overview of performance, cost and readiness levels for capturing carbon from ethylene production

Feedstock	Coal
CO_2 avoidance cost (USD/tCO_2 avoided)[23]	203
CAPEX (USD/t)	565–1 130
TRL	5
Commercial availability	2030–2035

Source: Based on Szczeniak et al. (n.d.).

22 Consists of costs for capturing the carbon and does not include transport or storage costs.
23 Consists of costs for capturing the carbon and does not include transport or storage costs.

Integration of biomass with capture in industries

The BECCS process captures and stores the released CO_2 resulting in 'negative' emissions. It is a combination of biomass conversion into heat, electricity or fuel, coupled with CCS technology. The advantage of BECCS is its potential to be retrofitted into existing industrial processes via biomass co-firing. As such, it could offer a transition pathway to the full use of biomass coupled with CCS. However, the integration of biomass into the industrial processes represents a challenge in itself. Currently, plants address either the use of biomass in their processes or focus on the integration of CCS, but barely focus on both. Understanding the routes and challenges associated with the integration of biomass into industrial processes to be later coupled with CCS would represent a viable start.

Several routes are suitable for the conversion of biomass into fuels and feedstock to be used in industries in combination with CCS. These include the production of bio-feedstocks, biochemical and thermo-chemical production of biochemicals, and biomass combustion for the production of electricity and/or heat (ZEP and EBTP, 2012). However, carbon efficiency and energy efficiency[24] are different when biomass is used for fuels for power (Table 8). The power route is more energy efficient than the biofuel route, while the biofuel route is more carbon efficient than the power route (Fajardy et al., 2019).

TABLE 8: Carbon and energy efficiency for different methods of biomass integration

	Energy efficiency	Carbon efficiency
Biomass to power	11%	50%
Biomass to fuel	6%	25%

Source: Based on Fajardy et al. (2019).

Raw biomass cannot be used directly in these processes for several reasons – such as low calorific value, low density and high moisture content – and needs to undergo pre-treatment before it can be integrated into industries. There are also different types of biomass, with varying thermal properties that affect their performance to generate energy after combustion.

Cement production

Biomass can be used directly in cement plants as an energy source in preheaters and/or precalciners in either solid form or after being converted into gas. As biomass has a lower calorific value, larger quantities are required to replace fossil fuels. For instance, to replace one litre of fossil fuel requires four kilograms of biomass (Seboka, Getahun and Haile-Meskel, 2015). Besides, cement plants require pre-treatment infrastructure for biomass, which imposes additional costs.

Biomass can be also integrated with coal to supply heat to the pre-calciner and the kiln, reducing the consumption of coal and therefore emissions, if the plant is not equipped with capture technology. The fly ash from the co-firing plant can also be used to produce clinker, and as an additive when grinding cement. With 30% biomass integrated with coal (Table 9), the estimated avoided costs of CO_2 vary depending on the technology used: for post-combustion using MEA solvent the estimated avoided costs are in the range of USD 87–104/tCO_2; for post-combustion using calcium looping the estimated avoided are USD 64–74/tCO_2; for oxy-fuel combustion the estimated avoided costs are in the range of USD 50–72/tCO_2 (Sanmugasekar and

24 Carbon efficiency is defined as the fraction of carbon fixed in biomass that becomes net-negative. Energy efficiency is fraction of primary biomass energy that is converted into useful energy, considering lifecycle energy inputs and outputs.

Arvind, 2019). When compared with 100% fossil fuel use, post-combustion using MEA solvent is cheaper with 30% biomass; using calcium looping seems similar and, in some cases, cheaper; while oxy-combustion is more expensive with biomass.

TABLE 9: Comparison of costs of avoided CO_2 for fossil fuel-based CCS and BECCS

USD /tCO_2[25]	MEA	Calcium looping	Oxy-combustion
100% fossil fuel	107	20–75	44–46
30% biomass + 70% coal	87–104	64–74	50–72

Source: Based on Sanmugasekar and Arvind (2019).

Iron and steel production

The use of biomass as a source of energy or reducing agents can provide an alternative for blast furnaces but poses technical and economic challenges that require further investigation. Coke is an unavoidable raw material for the BF-BOF route, and due to its properties cannot be fully replaced. Its partial substitution with biomass can be introduced at three stages: coke-making, sintering and in blast furnaces.

The production of bio-coke requires biomass pre-treatment to reach the desired physical and chemical properties (fixed carbon, volatile matter, etc.). Biomass can then be added to coal with typical levels in the range of 2–10%. Any higher levels would impair coke quality (Mousa et al., 2016). Further possibilities to increase biomass would require additional research for large-scale production.

In the sintering process, partial substitution of coke breeze with biochar is possible, at a 60% maximum, to achieve similar sinter yield and productivity as coke breeze. In addition to reducing fossil fuel CO_2 emissions, it would effectively mitigate SO_x and NO_x (Mousa et al., 2016). Raw biomass is not suitable due to its high moisture, low carbon content and low calorific value, and requires pre-treatment before utilisation.

Biomass potential is largest in blast furnaces, where it can be introduced in several ways, either through top-charging (bio-sinter, bio-composite, torrefied materials, charcoal) or injection through tuyeres (pulverised biochar, ground torrefied materials, bio-oil, bio-PCI) (Mousa et al., 2016). Charcoal can fully replace only pulverised coal in the blast furnace, in all other cases the substitution of coke with charcoal is limited to a maximum of 20%.

When integrating with capture, a study assessed costs of avoided CO_2 when integrating biomass in iron and steel production in the range of USD 66–110/tCO_2 for plants located in the European Union (Mandova et al., 2019).

The maximum CO_2 emissions reduction potential with biomass blending is around 42%, but it will also incur high costs, with a roughly 50% increase of the steel price (Mandova et al., 2018). These costs are without factoring in the costs of CCS for the remaining CO_2 emissions. Current projects either focus on the use of biomass in iron and steel or the use of CCS; there is, however, a study that discusses the use of biomass in iron and steel production with CCS in five steel production routes. The study focuses on the mitigation potential of BECCS throughout the production chain, including sustainable biomass sourcing, but does not address the avoided costs (Tanzer, Blok and Ramirez, 2020). Brazil is currently the only country using 100% charcoal in small-size blast furnaces, but without CCS. The use of biomass in iron and steel production has been explored by Srivastava, Kawatra and Eisele (2013), who produced a self-reducing iron oxide and biomass composite pellet as a reducing agent; by the ULCOS project in Europe; and by a Canadian programme run by Canadian Steel Producers Association (CSPA) and Arcelor Brazil, but without CCS.

25 Consists of costs for capturing the carbon and does not include transport or storage costs.

Chemicals production

Biomass can be integrated as feedstock in the chemical value chain. For this, the feedstock is dried, ground, and gasified with oxygen and/or steam (ZEP and EBTP, 2012). The gas is cleaned and processed to form syngas, which can be used in commercial conversion processes such as Fischer–Tropsch to produce chemicals. Integrating biomass in this way leads to direct net-zero emissions, as the CO_2 emitted during synthesis is recycled as feedstock (Gabrielli, Gazzani and Mazzoti, 2020). The costs of producing chemicals via this route are much higher than standard CCS. The comparison of costs to produce ammonia and methanol with CCS or biomass (without CCS) is depicted in Table 10. The advantage lies in the reduced CO_2 emissions, which are present in the case of the standard capture. There is limited research on the process and economics of capturing emissions when biomass is used as feedstock to produce chemicals. In theory, this kind of arrangement has the potential to deliver net-negative emissions from production.

TABLE 10: Comparison of biomass-based and CCS routes for the production of ammonia and methanol

Feedstock	Ammonia			Methanol		
	Coal with CCS	Natural gas with CCS	Biomass	Coal with CCS	Natural gas with CCS	Biomass
Cost of product (USD /t)	350–650	250–650	1 000–1 600	350–550	200–500	900–1 500
Emissions intensity (tCO_2/t)	2	1.2	0	0.3	0.1	0

Source: Based on IEA (2019).

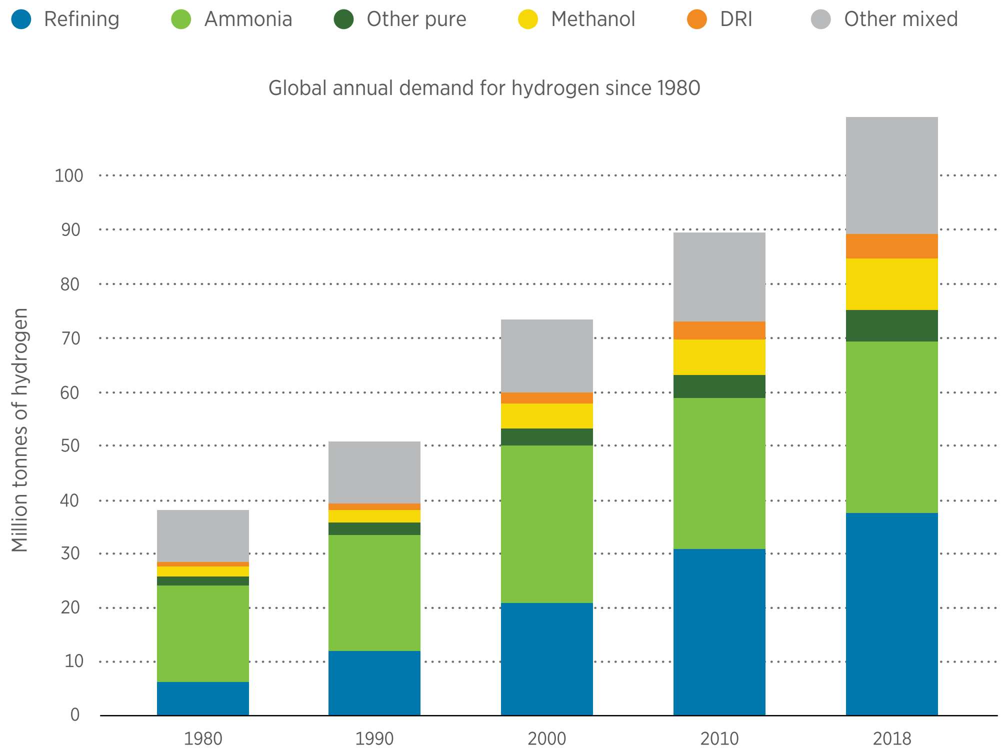
Production of biofuels from chemicals can provide attractive opportunities for expanding the integration of biomass in this industry. Production of bioethanol and CCS is a mature technology and operates at large scale at the Illinois Industrial CCS facility, capturing 1 Mtpa CO_2. There are several other small-scale and demonstration projects that capture 0.1–0.6 Mtpa of CO_2. It is usually produced by fermentation of biomass, during which micro-organisms metabolise plant sugars to produce ethanol. Roughly two-thirds of CO_2 in the sugar remains in ethanol while the remaining forms a pure stream of CO_2 (~98–99%), which is captured using gas processing, and then compressed and stored (ZEP and EBTP, 2012). One study assessed costs of avoided CO_2 capturing carbon from ethanol production to be USD 22–28/tCO_2 (Irlam, 2017).

However, life-cycle emissions have to be low for the liquid biofuel to be carbon negative. This is because less CO_2 is captured upon the conversion of biomass to liquid bio-fuels. For instance, in the case of ethanol, the captured process emissions account for just 15% of biomass carbon content (Fajardy et al., 2019).

2.5 Blue hydrogen production

Blue hydrogen refers to grey hydrogen produced from fossil fuel, which is combined with CCS. It is produced by steam methane reforming (SMR) or auto thermal reforming (ATR), and in the case of coal, through coal gasification. Blue hydrogen has already been already used as a fuel or feedstock. Figure 30 shows that the demand for hydrogen has been growing since the 1980s from below 40 Mt of hydrogen in 1980 to almost 120 Mt in 2018. Since there are no additional capture costs, the ammonia production process is among the lowest-cost options for CCS deployment. The economic outlook, however, changes if dedicated additional hydrogen production from fossil fuels is considered.

FIGURE 30: Hydrogen use trends, 1980–2018



Source: IRENA, 2019.

Figure 31 illustrates that there are three commercial plants currently operating in the United States and Canada, capturing 5 Mtpa of CO_2. The remaining projects are due to be finalised between 2021 and 2030, potentially capturing an additional 23.6 Mtpa of CO_2. These projects are located in Europe and India. There have been three pilot and demonstration projects: the Tomakomai project in Japan was completed in 2020 without any commitments to continue as a commercial site. The UK and Norway's pilot and demonstration projects are in the early stages of development.

FIGURE 31: Blue hydrogen CCS projects

- ● Pilot and demonstration
- ● Commercial

Facility	Location	Capacity Mtpa/CO_2	Status: Early development	Advanced development	Under construction	Completed	Operating
Acorn CCS	UK	0.2	●				
Air Products SMR	USA	1					●
Coffeyville Gasification	USA	1					●
Great Plains Synfuels Plant and Weyburn-Midale Project	USA	3					●
H-vision	NL	2	●				
H2Gateway - Port Den Helder	NL	2	●				
H2H Saltend	UK	1.4	●				
H2M Magnum	NL	2	●				
H2tomorrow	DE	1.9	●				
HyDemo	NO	-	●				
HyNet North West	UK	1.5	●				
HyPER project	UK	-		●			
Koyali refinery CCS	IN	0.25 - 0.5 (max 1.5)	●				
Pouakai	NZ	1	●				
Preem H2 Plant, Lysekil refinery - Northern Light	SE	0.5	●				
Quest	CA	1					●
Saga Pure	NO	-	●				
Southampton hydrogen super-hub	UK	-	●				
Tabangao Refinery Hydrogen Plant	PH	-	●				
Tomakomai	JP	0.1				●	
Yanchang Integrated CCS Demo project	CN	0.4			●		
Yanchang Integrated CCS Demonstration project	CN	0.05					●

BR - Brazil, CA - Canada, CN - China, DE - Germany, IN - India, JP - Japan, NL - Netherlands, NO - Norway, NZ - New Zealand, SE - Sweden, PH - Philippines, UK - United Kingdom, USA - United States.
Source: Based on Burnard (2019); MIT (2016).

Costs

When producing hydrogen, the CO_2 needs to be separated from the H_2 gas. Therefore, no additional capture costs arise for CCS except for the pressurisation of CO_2. As per the current industry standard (Table 11), CO_2 is captured from the shifted syngas using MDEA solvent with a capture rate of 56%. CO_2 can also be captured from the gas using MEA solvent, resulting in a capture rate of 90% (IEAGHG, 2017c). This technology is commercially viable and can be applied to large-scale hydrogen production, although at higher production costs than the current standard. Standalone blue hydrogen comes at higher costs and seems uneconomical in the absence of industrial hubs and infrastructure for transportation and storage (Gaffney Cline, 2020).

TABLE 11: Overview of performance, cost and readiness levels for capturing carbon from standalone hydrogen production

	MDEA	MEA
Capture rate	55.7%	90%
CO_2 avoidance cost (USD /t CO_2)[26]	53	79
CAPEX (USD/[Nm_3 /H_2])	2 655	3 560
Cost of product (USD/kg)	1.76	2.05
TRL	9	6–9
Commercial availability	Current industry standard	2025

Source: Based on IEAGHG (2017c).

26 Consists of costs for capturing the carbon and does not include transport or storage costs.

ANNEX

C

STATUS AND POTENTIAL FOR THE TRANSPORTATION OF CO_2

CO_2 transport applies to both the CO_2 captured from fossil fuel-based processes as well as from CDR measures – biomass with carbon capture and direct air capture.

Captured CO_2 requires **compression, liquefaction**, **solidification or hydration before** being **transported** to a storage or a utilisation site. The choice is linked to the transport mode and depends on several factors: the quantity of CO_2 transported, the distance to the storage or utilisation site, technology maturity and associated costs, and social acceptance of the particular transport mode in the area.

Since transport is a link between CO_2 capture and storage sites, synergies need to be respected by all three stages (capture, transport and storage), in terms of design and material selection as well as operation, how to reduce over-design and costs, while taking into consideration hubs, clusters and networks (Annex D - Box 5) to avoid under- or over-capacity as well as safety standards.

Compression and liquefaction are established technologies with accumulated knowledge and experience from the oil and gas sectors. There are more than ten compression technologies, which vary in terms of their energy savings and associated costs. Compression technology may require 80–120 kWhe/tCO_2 (Jackson and Brodal, 2019).

Solidification is also a commercially viable option, but it is more energy- and cost-intensive than previous options. Researchers are exploring activities that are both more cost- and energy-efficient and scalable, including converting the gaseous CO_2 into a solid carbon by using liquid metals as a catalyst at room temperature (Esrafilzadeh et al., 2019).

Hydration is the least developed technology. Current research and development activities focus on natural gas hydration to replace LNG and its use for CO_2 may be considered in the future (IPCC, 2005b).

3.1 Transport modes

There are several possible transport modes, such as pipelines (offshore and onshore), shipping and landways (railway and trucks). Their suitability depends on costs, which are dependent on flowrates and distances, but also on social and environmental considerations. Reaching the most cost-effective solution may require a combination of pipelines and ships, as well as the development of clusters, networks and hubs (Annex D - Box 5), to reach economies of scale to develop a large-scale infrastructure to support the scaled-up deployment of carbon capture.

Pipeline transport

Onshore and offshore pipelines are constructed in the same way as hydrocarbon pipelines, but inspection, venting, etc. can differ considerably. There are over 6 500 km of long-distance CO_2 pipelines worldwide, mostly associated with enhanced oil recovery (EOR) activities. Pipelines are concentrated mainly in the United States, which has transported circa 0.05 Gtpa of CO_2 since 1980 (IEAGHG, 2013c; IPCC, 2005b). The rest of the world has very limited experience with CO_2 pipelines. While the pipeline networks already exist both on land and underwater, to support longer-term CCS deployment globally, pipeline infrastructure must grow significantly in the next 30–40 years. The EU focuses on extending the useful lives of key infrastructure by repurposing existing and no-longer required gas and petroleum pipelines for captured CO_2, which could significantly reduce CAPEX and scale-up deployment of CCS projects (EC, 2019b).

To transport CO_2 through the pipeline, the CO_2 is in a supercritical state, with pressure greater than 74 bars and temperature greater than 31°C. Depending on the distance, it may require intermediate recompressions. There are also studies on transporting CO_2 in a liquid state at 10 bars and -40°C, but this requires additional pipe insulation.

The costs of construction of pipeline infrastructure to transport CO_2 over long distances are high (circa 90% of overall costs) and proportional to the distance. This can be mitigated by building shared infrastructure to benefit from economies of scale.

Ships

Ships are an alternative option suitable for longer distances (beyond 1 000 km), offshore storage and small distributed sources. Shipping of CO_2 has been driven by the food and beverage industry for the past 30 years, but volumes are much smaller than what is needed for CCS projects – they have a typical transport capacity of 1 000 m^3 and a trade flow of around 3 Mtpa. To carry larger volumes, there is a limited number of ships available. For example, Larvik Shipping has four liquid tankers with 1 200–1 800 tCO_2 capacity, while IM Skaugen has six carriers with the capacity to carry 10 000 and 40 000 m^3 of captured CO_2.

For demonstration projects, the use of ships to transport CO_2 may be more suitable, as it reduces the lock-in effect for projects, which may not continue past the demonstration phase and could therefore result in stranded assets (pipeline). The CO_2 is transported by ships in a liquid state at approximately 7–9 bara and -50°C to -55°C.

Ships are less capital intensive compared to pipelines as they are less dependent on distance and scale of transport, but OPEX (fuels, temporary storage, liquefaction, loading/unloading) make up a large portion of their total cost. Reducing these costs, as well as the design and operation of the injection system, and safety pose major technical challenges. Standards for safety are covered by the international gas code of the International Maritime Organisation.

Alongside technical and cost challenges, there are potential legislative difficulties in using ships for CO_2 transport in Europe. While CCS has been included in the EU Emissions Trading Scheme (EU ETS) since 2013, CO_2 transported by ship would be counted as released and not stored CO_2. This is because while pipeline transport and storage in geological formations require emissions permit and monitoring requirements, this requirement excludes liquefaction processes, CO_2 shipping vessels and loading/offloading. Any opt-in solution is theoretically possible but poses further legislative and financial complications (Global CCS Institute, 2015).

Trucks and railway

The use of trucks and railways is possible for small quantities. Trucks are currently used at project sites to move CO_2 from the capture site to nearby temporary storage locations.

3.2 Costs

While costs of capture dominate the total CCS project costs, CO_2 transport costs can be significant. They tend to be modelled as lump sums that ignore the flowrate, distance to storage and utilisation sites, storage type and transport mode. They are also often modelled for large-scale plants with a high volume of CO_2 and disregard the smaller plants which may need a combination of transport modes and benefit from economies of scale through clusters, hubs and transport networks (Annex D, Box 5).

Very few studies (Freitas, 2015; Gao et al., 2011; ZEP, 2011a) have calculated costs by reflecting on capacity and distance to assess which transport modes, or combination thereof, are the most suitable. Gao et al., base their study on the China case, Freitas looks at trucks, and ZEP base their estimates on CCS demonstration projects and commercial natural gas-fired plants with CCS in Europe. For pipelines, CAPEX is a major component amounting to up to 90% of total transport costs. For ships, the situation is reversed, and a major component is OPEX for liquefaction, fuels, loading/unloading and temporary storage.

Costs vary depending upon the type of transportation, distance and capacity of CO_2 transported. For onshore pipelines, costs are in the range of USD 1.7–6.1/tCO_2 for distances between 180 km to 750 km with capacities ranging from 2.5 Mtpa CO_2 to 20 Mtpa CO_2. For offshore pipelines, costs are in the range of USD 3.8–32.4/tCO_2 for distances between 180 km to 750 km with capacities ranging from 2.5 Mtpa CO_2 to 20 Mtpa CO_2. Costs increase up to 58.4/tCO_2 for distances up to 1 500 km. For shipping, costs are in the range of USD 12.5–22.4/tCO_2 for distances between 180 km to 1 500 km with capacities ranging from 2.5 Mtpa CO_2 to 20 Mtpa CO_2. These estimates include liquefaction costs. For land-based modes, CO_2 can be transported using trucks and railways. Transportation of CO_2 using trucks costs USD 14.7/tCO_2 for distances greater than 100 kilometres with capacities ranging from 15 tpa CO_2 to 20 tpa CO_2. For railways, 1.46 Mtpa can be transported up to a distance of 600 kilometres at a cost of USD 8.2/tCO_2 (Freitas, 2015; Gao et al., 2011; ZEP, 2011a).

ANNEX D

STATUS AND POTENTIAL FOR CO_2 STORAGE

CO_2 storage applies to both the CO_2 captured from fossil-fuel-based processes and CDR measures – biomass with carbon capture and direct air capture.

Injecting and storing CO_2 is not a new or emerging technology and is already viable at industrial rates for 1 Mtpa CO_2 or more. Knowledge and experience have also improved in the past decades on the behaviour of CO_2 in different geological formations, and on the types of chemical and physical interactions between CO_2 and water, minerals, etc.

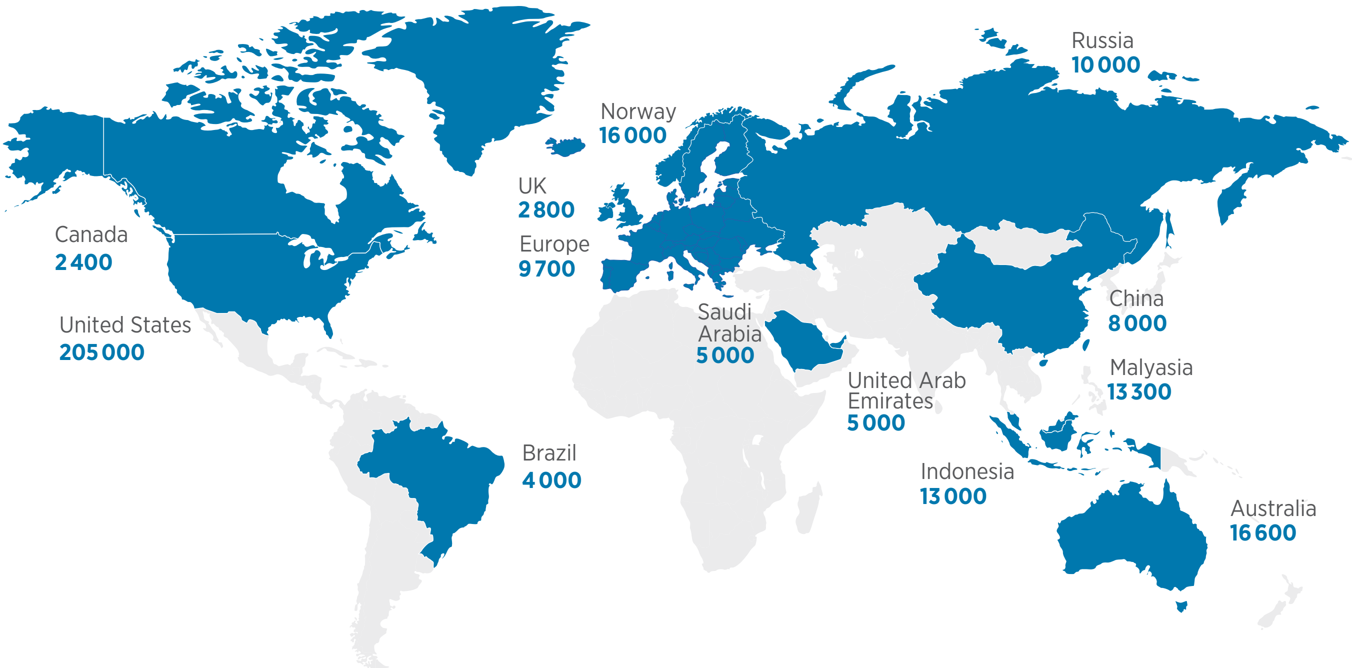
Missing elements are the policy and regulatory frameworks to store CO_2 at Gtpa levels, and an understanding of the costs and their categorisation across project phases from site screening, site selection, permitting and construction, to operation, post-injection (monitoring, evaluation, etc.) and closure. One of the ways to share and increase confidence would be through publicly available sources to allow for direct comparison, which are currently absent.

According to the CO_2 Storage Resource Catalogue launched in 2020, there are more than 12 000 Gt of potential unverified CO_2 storage resources globally (OGCI, 2020). Of these, around 400 Gt of storage sites are verified through data and analysis. Over the next five years, a major effort will be needed to technically assess every major CO_2 storage basin in the world. Yet, even with these efforts, certain key countries (e.g. India, Japan) are already known to lack the necessary rock formations to support large-scale CCS. Figure 32 provides an overview of CO_2

storage resources in oil and gas fields. According to the Global CCS Institute (2020), geological storage for CO_2 in saline formations is hundreds of times larger than oil and gas fields, with current data supporting the view that 98% of global storage resources are in saline formations. While these are all potential resources, true storage capacity will depend on technical, economic, environmental and social considerations and will be significantly lower. Figure 33 provides an overview of the results of storage resource assessments in major economies.

There have been some discussions about the leakage of CO_2 from reservoirs where it is stored. However, leakage of CO_2 represents the lowest risk identified as a part of risk assessment for storage projects (Deng et al., 2017). CO_2 is stored under a cap rock at a depth beyond 800 meters, which makes it dense, as high pressure restricts its movement. Catastrophic damage due to CO_2 leakages have not materialised.

FIGURE 32: CO_2 storage resources (millions of tonnes) in major oil and gas fields (excluding saline formations)

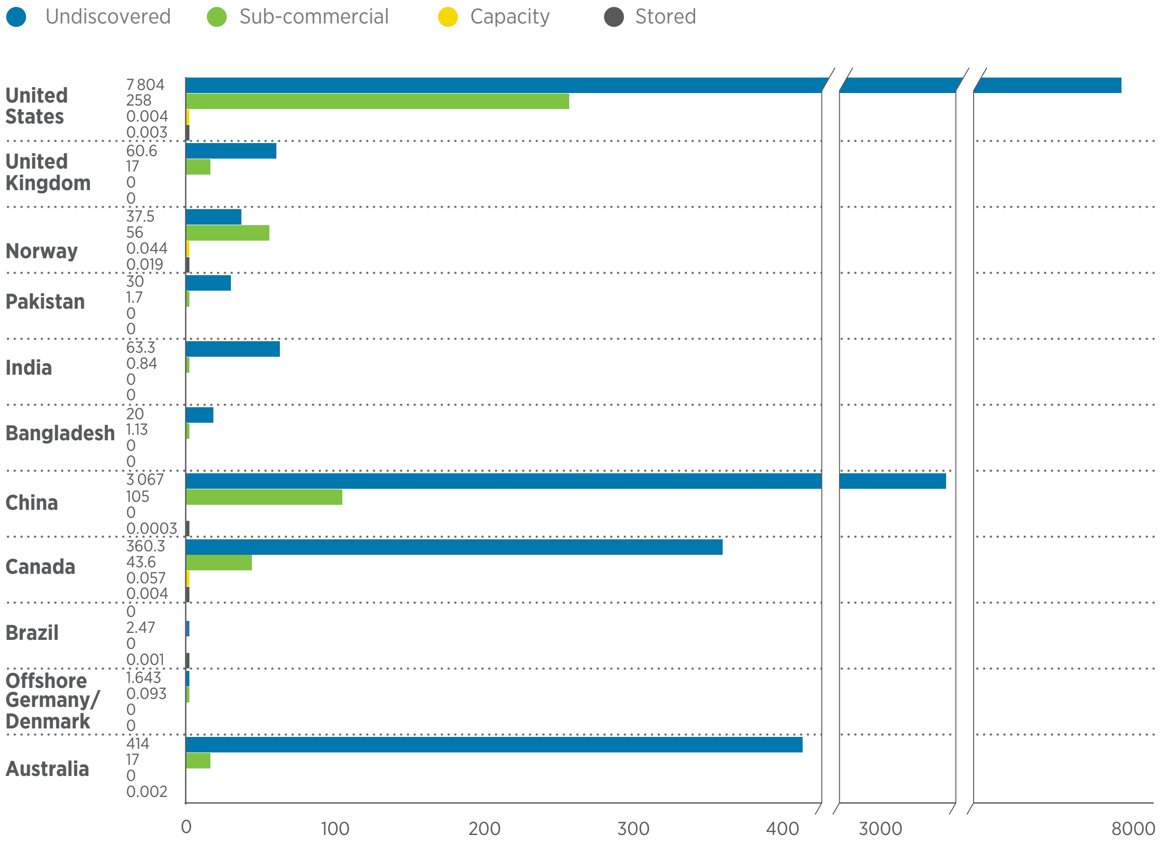


Source: (Global CCS Institute, 2020a).
Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.

Geological storage requires injecting captured CO_2 into rock formations deep underground that have suitable geological characteristics. These are formations that trap oil and gas, coal deposits, sandstones and dolomites.

There are several types of storage projects. A majority of existing CCS projects are associated with enhanced oil recovery (EOR) and there are some in saline formations. A future scale-up of deployment is foreseen in saline formations due to its wider geographical distribution and capacity compared to oil and gas reservoirs. However, not all countries allow geological storage; some (such as Ireland or Estonia) have introduced a permanent ban, except for research purposes; others (such as Poland, Sweden, Austria or the Czech Republic) have prohibited CO_2 storage temporarily until the finalisation of demonstration and deployment projects, in order to establish a better understanding of risks. According to the 2019 report from the European Commission on the implementation of the CCS Directive, 80% of the saline formations in the EU are situated in countries with CO_2 storage bans (EC, 2019c).

FIGURE 33: Storage resource assessment in major countries ($GtCO_2$)



Source: (Global CCS Institute, 2020a).

EOR and saline formations are mature technologies operating at commercial scale, while enhanced gas recovery, enhanced coal bed methane, enhanced geothermal recovery and depleted oil and gas fields have not yet reached maturity and are rated at around TRL 7.

4.1 Types of storage

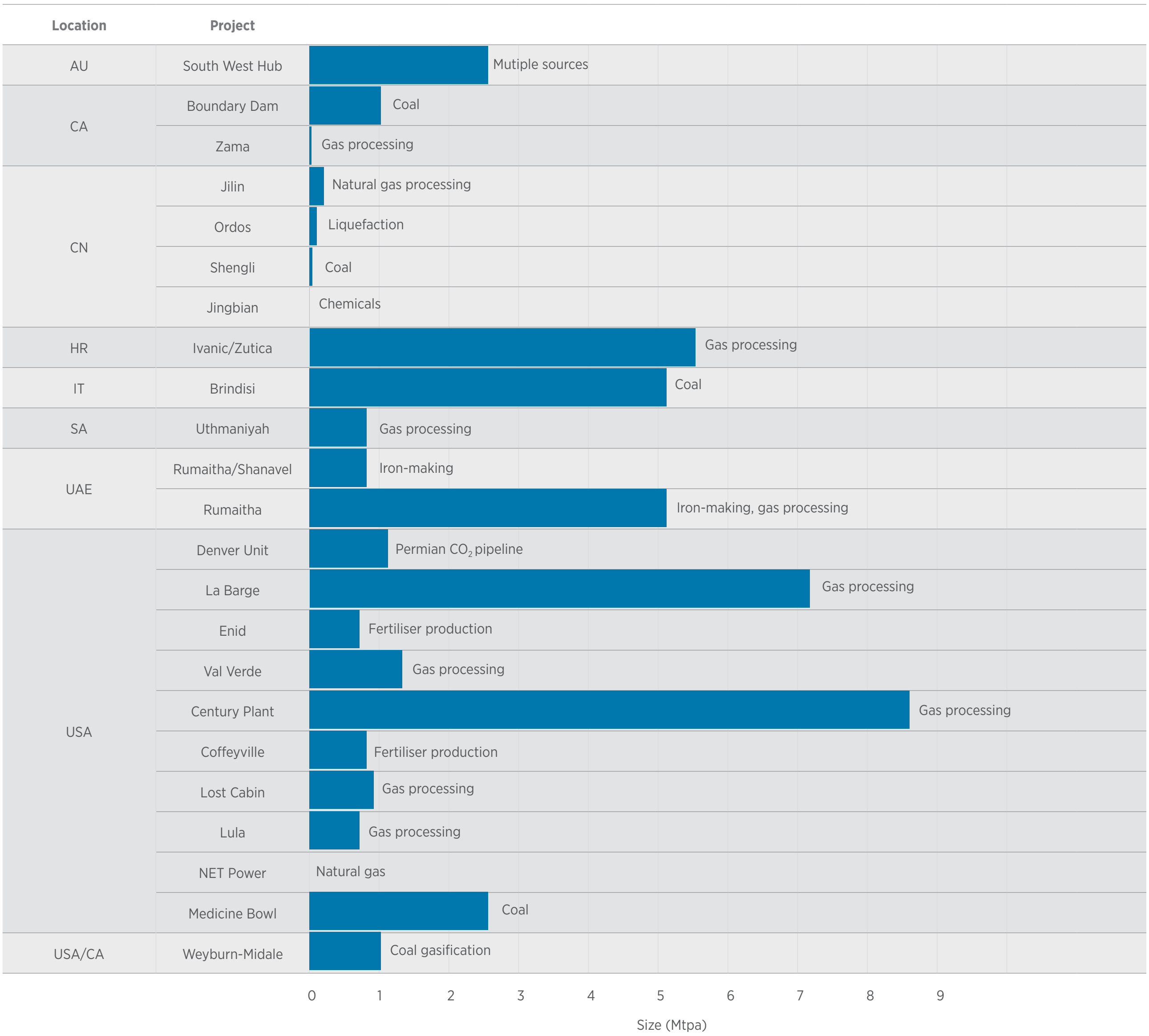
Enhanced recovery of hydrocarbons

The injecting of CO_2 can be further utilised to extract oil and gas, with part of the CO_2 trapped and later extracted with oil and gas, while the unextracted CO_2 is stored in depleted oil and gas fields. The process offers to offset investment costs through revenues from producing oil and gas. The CO_2 extracted with oil and gas is also addressed in Annex E on CO_2 utilisation. The issue is that the technology is not predominantly concerned with CO_2 storage, but rather with minimising net CO_2 injection and maximising oil recovery. This is particularly the case during periods of low oil prices and high CO_2 prices. For a process to be viable for high volumes of CO_2, a paradigm shift is required.

CO_2-enhanced oil recovery (EOR)

CO_2 has been injected into oil fields since the 1970s, with the first engineered injection of CO_2 for EOR carried out in Texas. EOR is a set of techniques for reservoirs with declining oil production to either maintain or improve oil production and thus extend their productive lives by decades. CO_2-EOR is only one of the EOR pathways, others are chemical, thermal or use other gases. In CO_2-EOR, the CO_2 is trapped and later extracted as oil, and the large portion of the CO_2 that does not mix with oil is stored permanently. As CCS is capital intensive, using CO_2-EOR creates revenues. An additional incentive for the use of CO_2-EOR can come in the form of tax credits (e.g. in the United States under Q45). There are currently 23 projects storing CO_2 in EOR with a total capacity of 0.03 Gtpa (Figure 34).

FIGURE 34: Overview of some of CO_2-EOR commercial and demonstration projects (ongoing, completed and planned)



AU - Australia, CA - Canada, CN - China, HR - Croatia, IT - Italy, SA - Saudi Arabia, UAE - United Arab Emirates, USA - United States.
Source: Based on EC (2021); Global CCS Institute (2020a); MIT (2016).

Enhanced gas recovery (EGR)

While EOR has been studied and the technology deployed for over 40 years, EGR is a novel approach and has never been tested. A large proportion of natural gas is left in reservoirs after depletion and referred to as trapped gas – including both residual and unswept gases. When injected, CO_2 pushes natural gas to the production wells.

The depletion of gas fields makes them more permeable, which may result in potential mixing of CO_2 with the remaining gas, possibly reducing the quality of produced gas significantly, even though this mixing is not very extensive.

Enhanced coal bed methane (ECBM)

Enhanced coal bed methane is another option for storing CO_2. The method produces additional coal bed methane from source rock. CO_2 is injected into the coal bed, spreads into pores and is adsorbed onto the carbon in the coal. It is an immature technology and faces major technical hurdles for its commercial deployment – particularly low initial injectivity and permeability loss during the injection. ETH Zurich is conducting research to study the process. There is only a single demonstration project in China at the Shanxi coal-powered plant, which is in the early stages of development.

Enhanced geothermal systems (EGS)

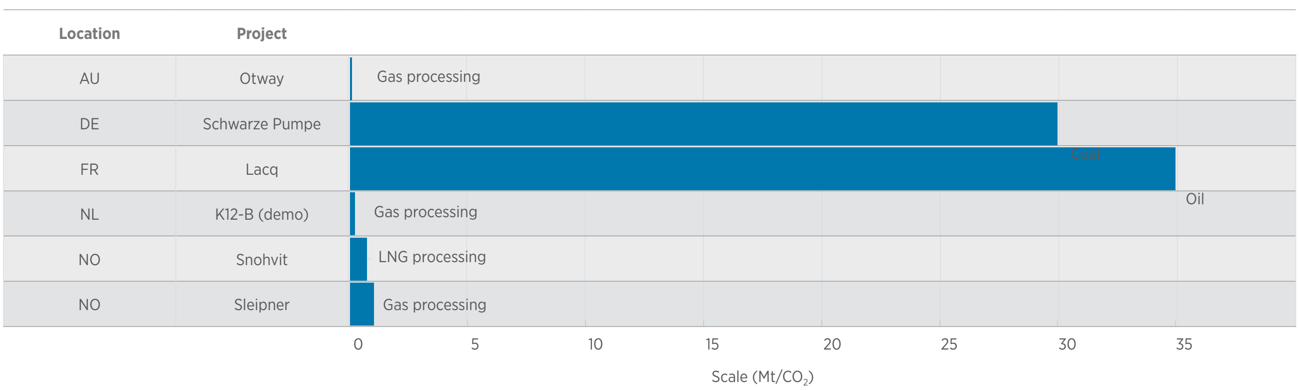
Due to its thermodynamic and hydrodynamic properties, captured CO_2 is being considered as a heat transmission fluid for geothermal extraction instead of water. This can reduce the large amount of water used for geothermal operation, as well as power requirements, and would both offer environmental and commercial value, and contribute to offsetting the CCS costs. Lost CO_2 during the heat extraction is stored as carbonate, which prevents it from escaping and moving to shallow aquifers or entering the atmosphere. The technology is currently at a lab-testing stage. There is a consensus that it is a promising alternative, but there are still numerous issues being investigated concerning its suitability and safety.

Depleted or disused oil and gas fields

CO_2 can be stored in depleted or disused oil and gas fields. The location, overall capacity and properties of these fields – such as porosity, permeability, pressure and temperature – are known, and equipment installed on the surface or underground may be re-used for CO_2 storage. Depleted gas fields are an important target for RD&D as they may represent a globally significant storage resource, but there have been few direct measurements to date to support this conclusion.

This storage option is not a mature technology. There are several demonstration projects (Figure 35) in the pipeline aiming to build public confidence, deepen scientific understanding and build technical knowledge.

FIGURE 35: Overview of some demonstration projects for CO_2 storage in depleted oil and gas fields



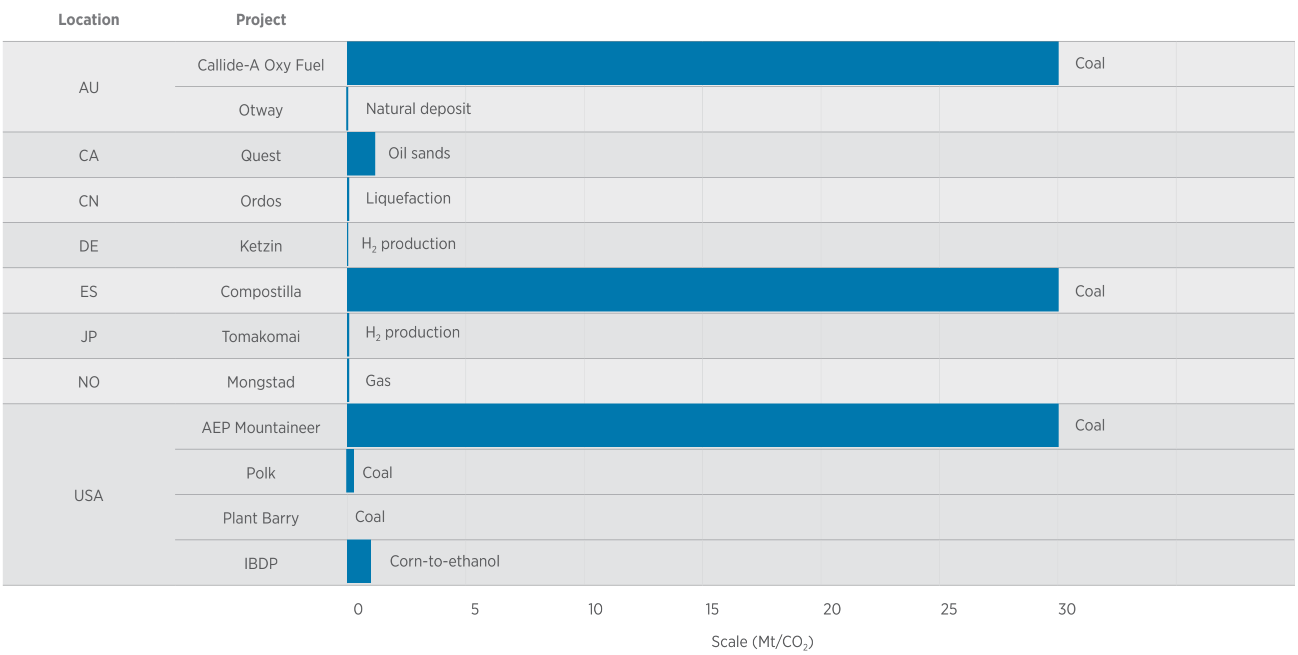
AU - Australia, DE - Germany, FR - France, NL - Netherlands, NO - Norway.
Source: Based on EC (2021); Global CCS Institute (2020a); MIT (2016).

Saline formations

Saline formations have the largest identified storage potential, with estimated storage capacity sufficient to store emissions from large stationary sources for at least a century. They are similar to oil or gas fields, but instead of hydrocarbons, they contain poor quality water, which is much more widely spread. Since saline formations have little or no economic value, there has been very limited investment in researching and assessing their storage potential.

There are some limitations to saline CO_2 storage capacity that relate to the pressure build up in aquifers that may adversely impact its effective storage capacity. Some studies (Thibeau and Mucha, 2011) suggest basing storage efficiency on a pressure approach rather than on a volumetric approach, and to extract formed water from the aquifer and either inject it elsewhere or treat it at the surface.

FIGURE 36: Some projects storing CO_2 in saline formations



AU - Australia, CA - Canada, CN - China, DE - Denmark, ES - Spain, JP - Japan, NO - Norway, USA - United States.
Source: Based on EC (2021); Global CCS Institute (2020a); MIT (2016).

CO_2 mineralisation in basalt

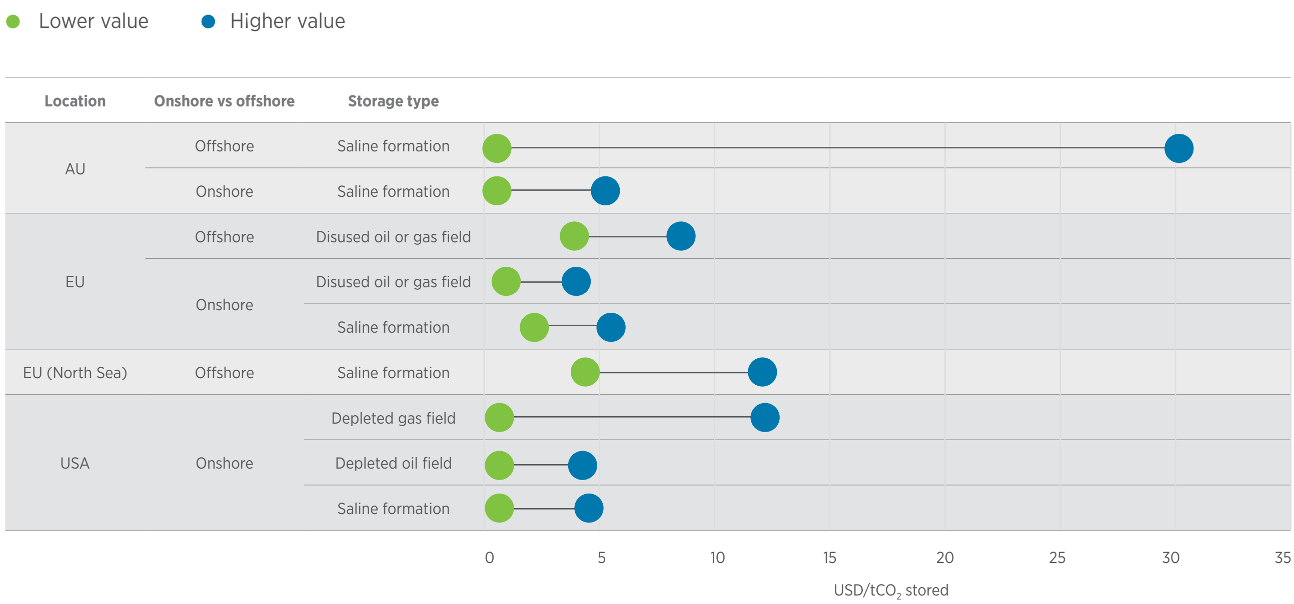
A very different way to store CO_2 permanently is through mineral carbonation. This is an engineered enhancement of carbonate precipitation, where CO_2 dissolves in water and is then injected into natural basaltic aquifers to form solid carbonate minerals. These act as permanent storage. The company CarbFix carried out its first pilot project in 2014 and since then the technology has reached commercial scale and has stored 70 kt to date (von Strandmann et al., 2019).

4.2 Costs

Data on storage costs are scarce. There is a lack of commercial deployment, and costs are very site-specific and are influenced by many factors such as location (country, onshore and offshore), type of storage, its quality, capacity and annual storage rate. There is a limited energy penalty for CO_2 storage. For storage to be economical, some studies (ZEP, 2011b) suggest the annual storage rate should be around 5 Mtpa for 40 years of storage resulting in circa 200 Mt of CO_2 of storage capacity.

The IPCC (2005a) Special Report on CCS analysed onshore and offshore depleted and disused oil and gas fields and saline formations in the United States, the European Union and Australia. Figure 37 provides an overview of these cost estimates, which include CAPEX, OPEX and site characterisation costs, but exclude monitoring, remediation and any other costs linked to long-term liabilities. Economies of scale have not been considered. Based on the IPCC report, onshore storage in saline formations is cheaper than offshore storage.

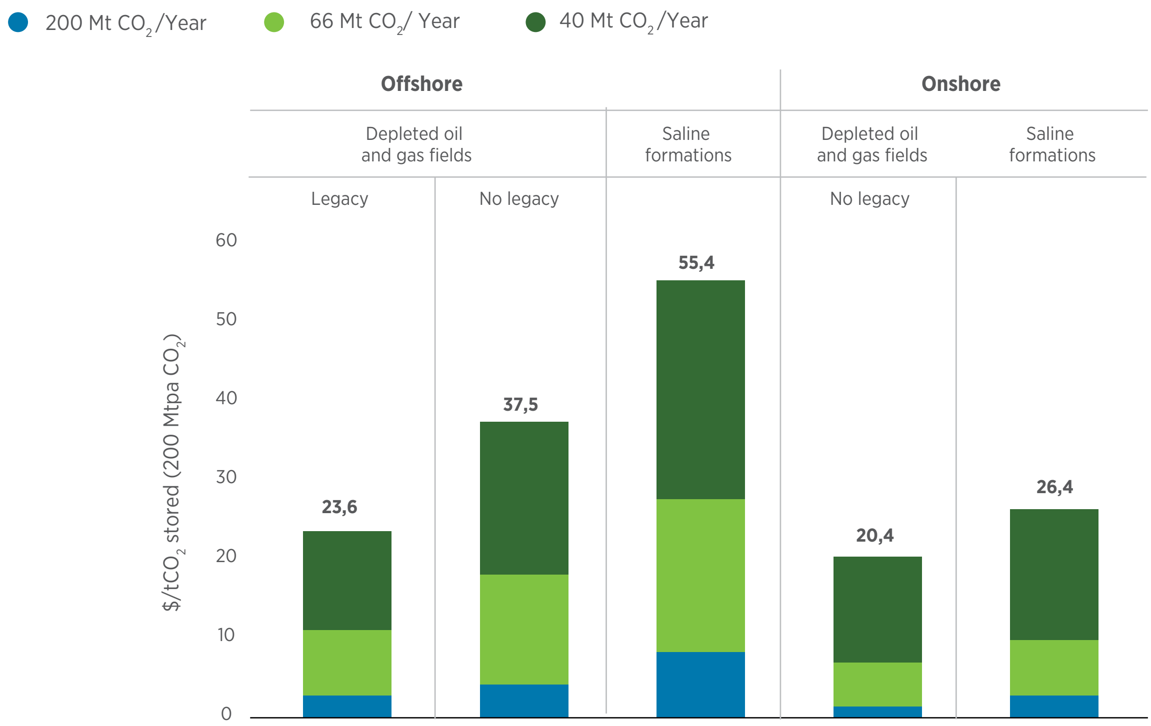
FIGURE 37: Overview of costs of storage (saline formations and depleted or disused oil/gas fields)



AU - Australia, EU - European Union, USA - United States.
Source: Based on IPCC (2005a).

The ZEP study (2011a) assessed the costs of storage in Europe based on the storage capacity for 40, 66 and 200 Mtpa of CO_2 (Figure 38). The costs also consider legacy wells (wells reused for injection or monitoring), which are a major component in both CAPEX and OPEX. For saline formations, total costs of building new structures are assumed, while in offshore depleted oil and gas fields existing structure is assumed. OPEX includes learning rate and CAPEX includes economies of scale. According to this study, the onshore storage is cheaper than offshore and depleted oil and gas fields, and cheaper than saline formations.

FIGURE 38: Overview of storage costs in Europe



Source: (ZEP, 2011b).

BOX 5:

CO_2 hubs, clusters and transportation networks

To lower barriers of entry for both small- and large-scale CCS projects, and benefit from economies of scale, CO_2 sources can be linked into hubs, clusters and transportation networks. An example of a small-scale CCS project is a cement plant that captures less CO_2 compared to steel or power plants and would benefit from sharing the last mile of transport to the storage site by joining hubs, clusters or transportation networks.

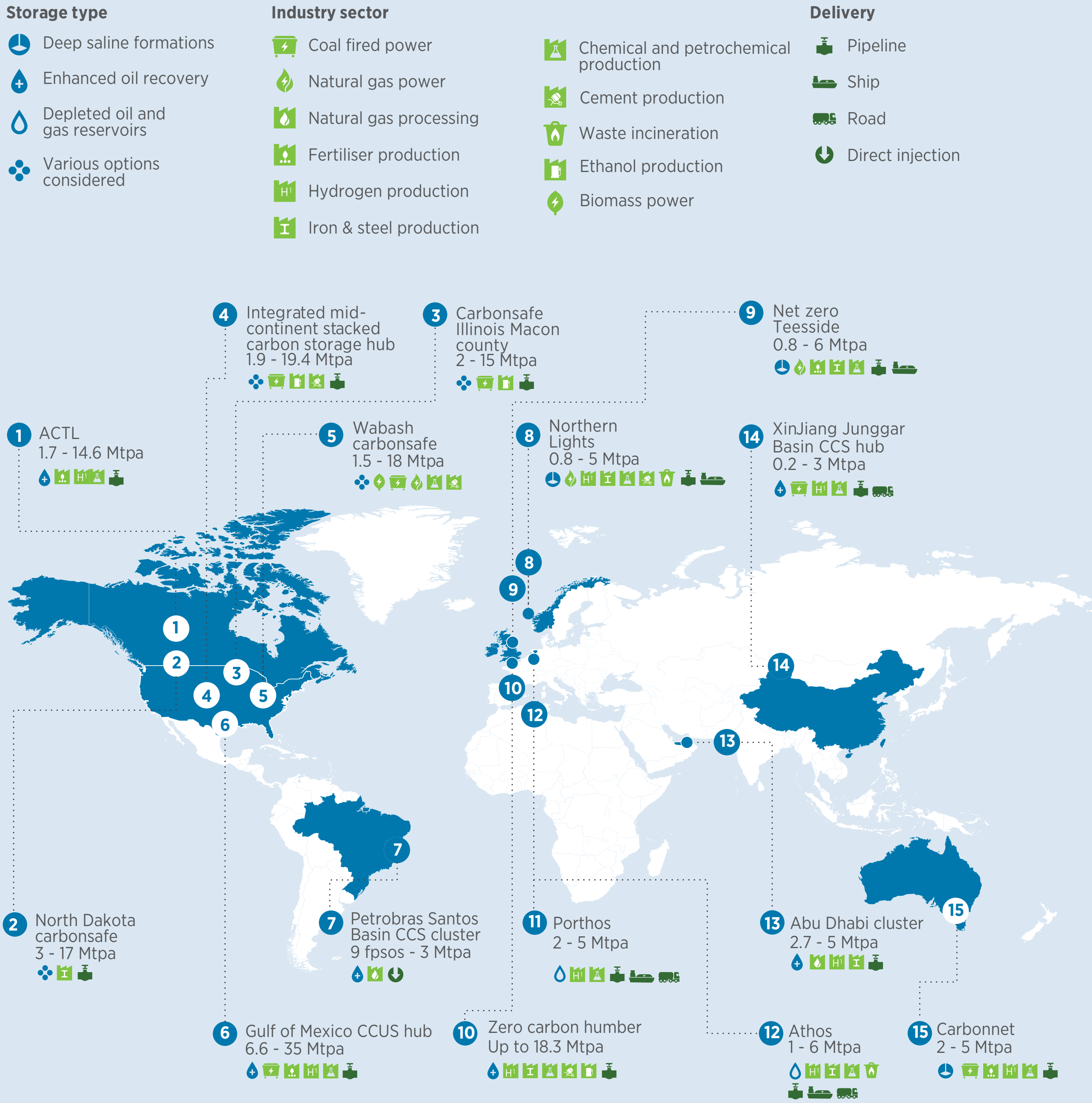
Hubs, clusters and transportation networks address several underlying issues, including methods to optimise the entire CCS cluster and engineer waste heat utilisation, but particularly to establish the same CO_2 standards between the capture plants of the hubs, and cluster and storage sites. Hubs, clusters and transportation networks (Figure 39) differ:

CO_2 hubs collect CO_2 from many sources and distribute it to single or multiple storage locations. An example is the South West Hub project in Western Australia. The Hub collects CO_2 from various sources into two industrial areas (Kwinana and Collie) in order to store the CO_2 in the Lesueur formation in the Southern Perth Basin.

CO_2 clusters group individual CO_2 sources or storage sites within a region. Such an example is the Permian Basin in the United States. It has several clusters of oilfields undergoing CO_2-EOR that receive CO_2 from a network of pipelines. In Denmark, the newly established Carbon Capture Cluster Copenhagen (C4) aims to jointly capture 3 Mtpa CO_2 and share the infrastructure for transport to the storage site (Falkengaard and Valeur, 2021).

CO_2 transportation networks are large collection and transportation infrastructures that provide access to multiple CO_2 sources. The European Union has built a large transportation network in its North Sea Basin, including the Northern Lights project.

FIGURE 39: CO_2 hubs, clusters and transportation networks in operation or development



Source: (Global CCS Institute, 2020a).
Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.

ANNEX E

STATUS AND POTENTIAL FOR CO_2 UTILISATION

To improve the economic feasibility of carbon capture by creating a revenue stream from captured CO_2 and to overcome a lack of readily available CO_2 storage sites, carbon capture and utilisation (CCU) is being considered by many sectors. CO_2 can be utilised to produce chemicals, fuels and materials. CO_2 has been utilised on a small scale by the food and beverage industry. The utilisation route is, however, not a preferred solution when aiming for net-zero emissions by mid-century, as the captured emissions will be released back into the atmosphere in the short or medium term. However, in the short term, it can be carbon-reducing by replacing carbon-intensive products with less intensive alternatives.

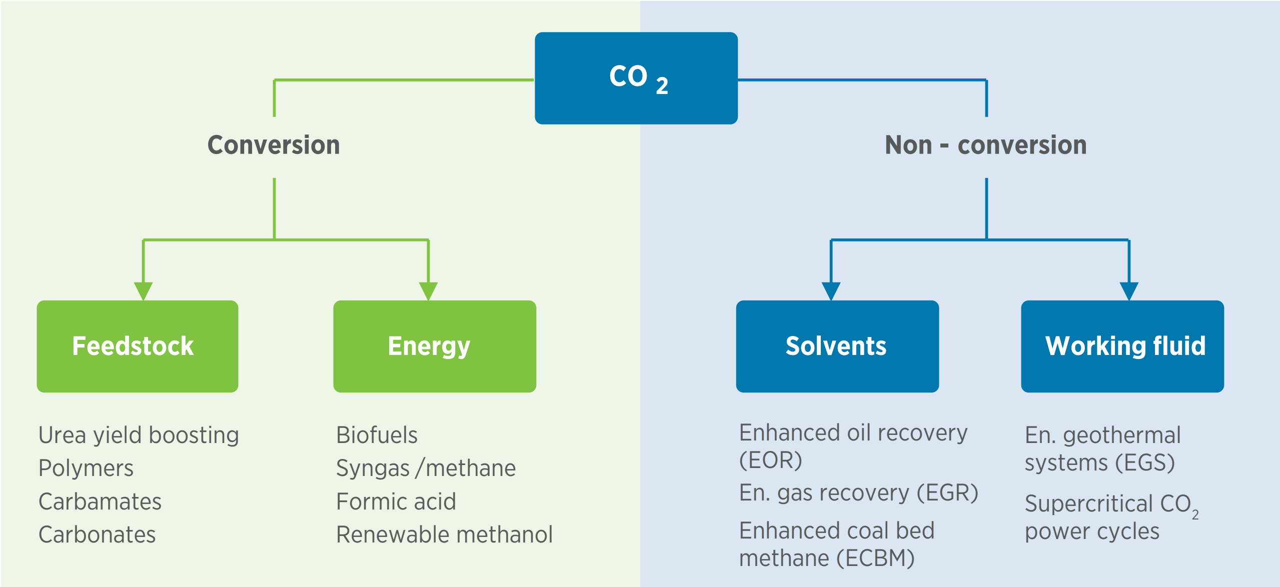
Carbon capture and utilisation entail a suite of technologies. CO_2 can be used as part of the conversion process to produce new products, as a solvent or a working fluid for various processes (Figure 40).

5.1 Categories of utilisation

Hendriks et al. (2013) further categorise utilisation by end-use applications:

- **CO_2 to fuels** includes production of energy vectors – syngas, hydrogen, renewable methanol, algae (to biofuels), photocatalytic processes, nanomaterial catalysts, etc. It can be reached through chemical or biological conversion. Excepting hydrogen, all these technologies are in the early stages of development (with low TRLs).

FIGURE 40: CO_2 utilisation applications



Source: (Hendriks et al., 2013).

- **Enhanced commodity production** covers commercially available technologies and methods where CO_2 is used to produce certain goods for which CO_2 is already used but could be modified (urea, methanol) or act as a substitute for existing technologies (steam in power cycles). The production of urea and methanol[27] is a mature application; power cycles using CO_2 steam are at low TRLs.
- **Enhanced hydrocarbon recovery** includes technologies that use CO_2 as a working fluid to increase recovery of hydrocarbons such as enhanced oil recovery (EOR), enhanced gas recovery (EGR), enhanced coal bed methane (ECBM) or enhanced geothermal systems (EGS). CO_2-EOR is a mature technology, while the remaining technologies (EGR, ECBM and EGS) are in the early demonstration stages (they are discussed in more detail in Annex D on storage, as the majority of CO_2 stays stored underground permanently).
- **CO_2 mineralisation** entails chemical weathering of certain minerals using CO_2 and is used in cement production for building aggregates and cementitious products, in CO_2 concrete curing, as well as for bauxite treatment and carbonate mineralisation. None of these applications are mature and all require additional RD&D efforts.
- **Chemicals production** includes photocatalysis or electrochemical reduction and is used in the synthesis of a range of intermediates for chemical or pharmaceutical productions. Some applications are mature but many are emerging, particularly to use CO_2 as a substitute in some production methods. Examples are sodium carbonate, polymers, algae (for chemicals) and other chemicals (acrylic acid from ethylene, acetone, etc.). None of these applications are close to maturity.

Several considerations will shape the scale-up of CCU:

- **Maturation of technologies:** a majority of these technologies are in the early RD&D stages and are both capital- and energy-intensive. This necessitates financial and policy support, including RD&D funding and incentives to involve the private sector.
- **Proximate location of capture and utilisation plants:** the location of plants capturing CO_2 needs to be in the vicinity of the utilisation plants to decrease high transportation costs. This can be mitigated by CO_2 hubs and clusters.

27 More on methanol can be found in IRENA's 2021 report, Innovation Outlook: Renewable Methanol.

- **Potential commercial market:** several studies (IPCC, 2005c; Parsons Brinckerhoff and Global CCS Institute, 2011) estimate potential demand for CO_2 in different applications: for the CO_2 as fuel, the potential demand is over 1.2 Gtpa of CO_2 and the CO_2 mineralisation amounts to 335–630 Mtpa of CO_2; for enhanced commodity production the potential is much lower and amounts to 12–65 Mtpa of CO_2, and the production of the chemicals is 7–37 Mtpa of CO_2. Based on these estimates, the uptake of CCU will mostly depend on the large-scale implementation of CO_2-based fuels, given the fact that the use of CO_2 in fuels is much larger than for chemicals or enhanced commodity production.
- **Social acceptance:** compared to transport and storage – particularly onshore – utilisation enjoys the broadest public acceptance.

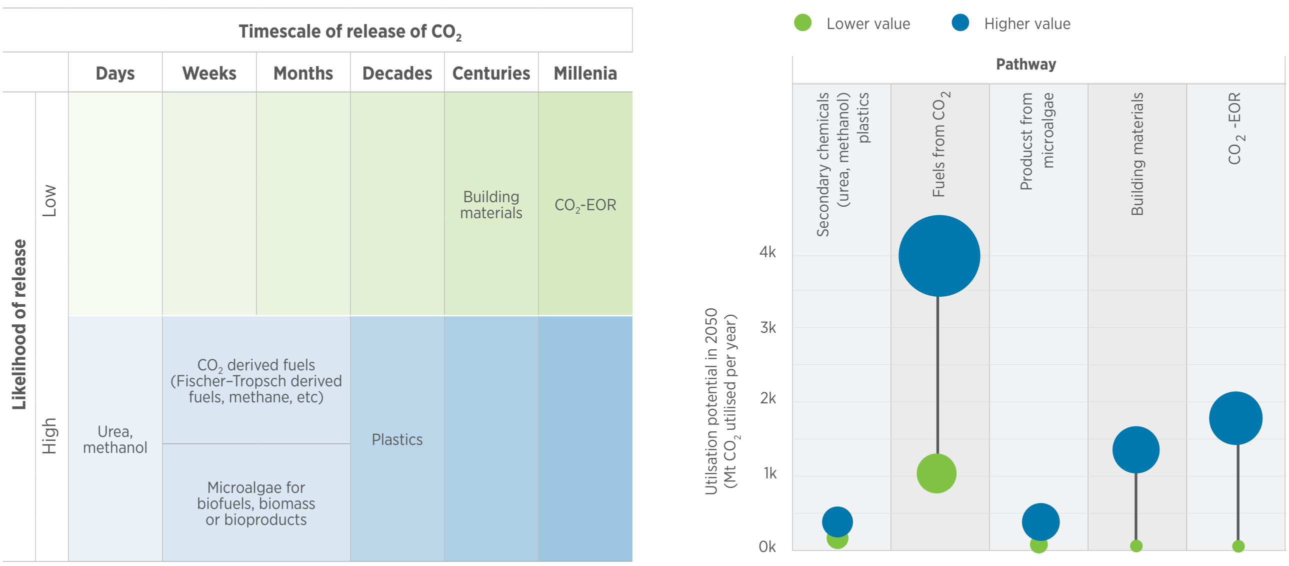
5.2 Re-emission of utilised CO_2 and its time-scale

The utilisation of captured CO_2 offers financial returns and is seen as a major incentive to scale-up the capture of CO_2 emissions. The CCU option is also pursued due to uncertainties surrounding the availability and accessibility of underground geological storage in the short term.

The utilisation of CO_2 poses questions about the long-term consequences of that utilisation, as it is difficult to trace CO_2 across multiple end-uses. For the CCU to be a viable strategy in the short term, numerous conditions need to be put in place: CO_2 should be utilised in products that lock-in CO_2 emissions for an extended period of time, and consider the timescale of lock-in and likelihood of CO_2 release (Figure 41). The examples are cementitious and other building materials, the use of CO_2 for enhanced fuel recovery (oil and gas but also coal or geothermal), where part of the CO_2 is used to extract oil or gas, while the rest of the CO_2 is stored long term. While plastics lock in the CO_2 for extended period, they will detrimentally affect the environment if plastic pollution is not managed well.

Further scepticism about lock-in effects is prevalent in chemicals, fertilisers, food and beverages, and fuels like ammonia or methanol where it is known that CO_2 emissions are emitted back to the atmosphere within days or weeks. Capturing CO_2 to produce these chemicals might not result in long-term environmental benefits. In the long-run, therefore, the utilisation cannot be considered a sustainable solution.

FIGURE 41: Re-emission of utilised CO_2



Source: Based on Hepburn et al. (2019).

ANNEX F

STATUS AND POTENTIALS FOR CDR TECHNOLOGIES (BECCS & DACCS)

6.1 BECCS and BECCU

Bioenergy with carbon capture and storage (BECCS) is a combination of biomass conversion into heat, electricity or fuel coupled with CCS technology. In conventional CCS, fossil fuels such as coal, petroleum or natural gas are burnt to produce heat and power which release large amounts of CO_2 that is subsequently captured and sequestered. BECCS, on the other hand, uses biomass as a fuel source. Biomass fixes atmospheric CO_2 for cellular photosynthesis during the growth period. At a reasonable stage, they are harvested and transported to processing facilities where the feedstock is converted to useful forms of bioenergy such as liquid biofuels, heat and power. The CO_2 resulting from those processes is usually released back into the atmosphere. However, the BECCS process captures and stores the released CO_2 resulting in 'negative emission' (Bioenergy Europe, 2019). BECCS has drawn interest as a versatile technology that has been considered as a 'safety net' due to its immense potential to capture CO_2 from various point sources such as pulp and paper plants, combined heat and power generation facilities, ethanol production units, waste-to-energy conversion sites, etc. and store it either in aquatic or terrestrial ecosystems that may be considered as vital carbon storage sinks (Fuss et al., 2018).

Advantages of BECCS

As mentioned above, since BECCS utilises an already carbon neutral biomass feedstock, capturing and storing the CO_2 released upon burning this biomass will further result in negative emissions. Moreover, employing BECCS instead of conventional CCS, apart from reducing GHGs, also promotes the production of low-carbon fuels and feedstocks, and renewable heat and power that can replace fossil fuels used in hard-to-decarbonise sectors. However, in the case of cement plants, the use of biomass to capture process-related CO_2 may result in a lower production rate (Sanmugasekar and Arvind, 2019). Another advantage of BECCS is that it can be retrofitted to energy-intensive manufacturing processes via biomass co-firing that would otherwise use 100% fossil fuels. BECCS also adds to the economy of a country in terms of increasing employment opportunities, encouraging biomass production and nurturing energy security (NASEM, 2019; Vaughan et al., n.d.).

Bioenergy with carbon capture and utilisation (BECCU) uses the captured CO_2 as a raw material for value-added products such as e-fuels, building/construction composites and chemical additives, instead of storing it in geological sites. Novel market opportunities are always on the table, considering such synergistic combinations of carbon-abating technologies (BECCS Task Force, 2018). However, given a limited supply of sustainable biomass, the use of biomass may be the priority for BECCS instead of BECCU.

Operating and planned BECCS/BECCU projects

Over the last decade, several projects have been sanctioned that are either operating at a full scale or are expected to take off in the next few years. Currently, there are 28 BECCS/BECCU plants – comprising either commercial or pilot and demonstration projects. The three operating commercial plants capture 1.13 Mtpa of CO_2, and with six more projects due between 2023 and 2030, an additional 6.73 Mtpa of CO_2 is expected to be captured. Out of 19 pilot and demonstration projects, six are completed, nine are operating and an additional four are under construction. Some plants also potentially use CO_2 captured for various manufacturing applications such as food, soft drinks, fire extinguishers and industrial solvents (more in Annex E). Plans for such plants are constantly evolving and often the status is commercially sensitive, so information is not publicly available. This list (Figure 42) is not definitive, therefore, but is indicative of the current status and near-term potential.

BECCS from an economic standpoint

A couple of challenges associated with scaling up bioenergy with carbon capture involve the costs of the technologies adopted and their corresponding energy efficiency (Fridahl and Lehtveer, 2018). Nevertheless, scientists are constantly pondering how BECCS may be rendered economically feasible. It has been ascertained that the costs vary depending upon the sector of application and a rough estimate is in the range of USD 12–288/tCO_2. As an example, for combustion units, the costs are USD 88–288/tCO_2; for biomass gasification plants costs are USD 30–76/tCO_2. Likewise, avoided costs for CO_2 from ethanol plants and gasification of black liquor from pulp/paper mills are about USD 12–22 per tonne of CO_2 and USD 20–70 per tonne of CO_2, respectively (Consoli, 2019; IRENA and Methanol Institute, 2021).

Some studies show higher estimates for bioenergy with carbon capture, as they assume the transport costs for biomass. In addition, the lifecycle emissions related to direct or indirect land-use add a 10–30% energy penalty to the costs, even if biomass is derived from land dedicated to biomass crops or cellulosic sources (Fuss et. al. 2019).

FIGURE 42: Non-exhaustive list of ongoing and planned BECCS/BECCU projects

- ● Pilot and demonstration
- ● Commercial

Facility	Location	Capacity Mtpa/CO_2	Status: In evaluation	Planning	Early development	Advanced development	Under construction	Operating	Completed
Alco Bio Fuel (ABF) biorefinery CO_2 recovery plant	BE	0.1						● Pilot and demonstration	
Arkalon CO_2 compression facility	USA	0.03						● Commercial	
Biorecro/EERC project	USA	0.005		● Pilot and demonstration					
BioZEG Plant	NO	-							● Pilot and demonstration
Bonanza BioEnergy CCUS	USA	0.1						● Commercial	
Calgren Renewable Fuels CO_2 recovery plant	USA	0.15						● Pilot and demonstration	
Cargill wheat processing CO_2 purification plant	UK	0.1						● Pilot and demonstration	
CLEANKER	IT	0.9						● Pilot and demonstration	
Domsjö Fabriker	SE	0.26	● Pilot and demonstration						
Drax BECCS project	UK	4			● Commercial				
Husky Energy Lashburn and Tangleflags	CA	0.1						● Pilot and demonstration	
Illinois Industrial Carbon Capture and Storage	USA	1							● Pilot and demonstration
Illinois Industrial Carbon Capture and Storage	USA	0.3						● Commercial	
Interseqt project - Herefort	USA	0.3			● Commercial				
Interseqt project – Plainview	USA	0.33			● Commercial				
Klemetsrud pilot	NO	0.0013							● Pilot and demonstration
Klemetsrud-Longship	NO	0.4				● Commercial			
Lantmännen Agroetanol purification facility	SE	0.2						● Pilot and demonstration	
Mikawa Post BECCS Plant	JP	0.2			● Commercial				
Mikawa Post Combustion Capture Demonstration Plant	JP	0.004						● Pilot and demonstration	
OCAP	NL	0.146						● Pilot and demonstration	
Saga City Waste Incineration Plant	JP	0.003						● Pilot and demonstration	
Saint-Felicien Pulp Mill and Greenhouse Carbon Capture Project	CA	0.01				● Pilot and demonstration			
Sao Paulo	BR	0.02							● Pilot and demonstration
Skåne	SE	0.005							● Pilot and demonstration
Södra	SE	0.8	● Pilot and demonstration						
The ZEROS Project	USA	1.5					● Commercial		
Yara-Longship	NO	0.21				● Pilot and demonstration			

BE - Belgium, BR - Brazil, CA - Canada, IT - Italy, JP - Japan, NL - Netherlands, NO - Norway, SE - Sweden, UK - United Kingdom, USA - United States.
Source: Based on CLEANKER (2018); Consoli (2019); EC (2021); MIT (2016).

The 1.5°C Scenario and necessary actions for the deployment of BECCS

In the 1.5°C Scenario, BECCS will play a role mainly in power plants, heat plants and the cement and chemical sectors, with 2.9 Gtpa of CO_2 captured and stored in 2040 and 4.7 Gtpa in 2050. This includes the carbon balance in the chemical and petrochemical industries through carbon stocks in chemical products, recycling and carbon capture in waste incineration. As a result, toward 2050, the power and industry sectors become net negative; i.e. the CO_2 captured more than compensates for remaining CO_2 emissions in those sectors.

Despite the commencement of notable BECCS facilities around the world, it is still not a fully commercialised technology and requires thorough improvements with regard to feedstock procurement, process economics and legislative support to reach the required capture potential by 2050 (Stavrakas, Spyridaki and Flamos, 2018).

Firstly, scaling up BECCS increases the demand for biomass feedstock. In many instances, this may lead to problems associated with forest degradation and conversion of arable land that supports food production into areas for biomass cultivation, representing a few among several contributing factors to land-use change. It is essential to not disrupt carbon stocks contained in these regions through such demoting practices (Fajardy et al., 2019). Thus, biomass has to be sourced in an environmentally and socially just way. Sustainable forest management, land restoration with bioenergy crops and an auxiliary focus on other potential residual feedstocks – such as agricultural and forestry residues, industrial waste streams, MSW and algae that could cater to the surging demand for raw material – can be adopted as viable sustainable sources to counteract any complexity that may occur due to intensification of biomass harvesting. Moreover, BECCS generally takes into account only the direct emissions that arise as a result of burning biomass, and less or no mention is made of any indirect emissions associated with biomass cultivation, harvesting, transportation, refining and capturing the resulting CO_2. A thorough lifecycle assessment of emissions related to the entire supply chain must be considered to evaluate the overall sustainability criteria of this technology (Babin, Vaneeckhaute and Iliuta, 2021).

Secondly, ways to achieve cost reductions for BECCS via a possible integration with existing CCS facilities should be considered. Biomass co-generation can be promoted amidst many existing coal-fired plants since it would be beneficial for emissions reduction and preserving energy efficiency, as well as to offset any energy penalties due to excessive use of fossil fuels (Kemper, 2017). Setting up BECCS plants very close to areas from where biomass is supplied is another way to reduce transportation costs and associated emissions.

Finally, adequate policy support is necessary for the successful implementation of BECCS. Notable initiatives in the form of carbon pricing, tax incentives for negative emissions and renewable energy certificates are prerequisites for it to rapidly develop in the coming years (Venton, 2016). There is no doubt that BECCS can stabilise climate concerns. However, it cannot be considered as the only solution and therefore needs to be complemented with the widespread deployment of several other CDR technologies including direct air capture (DAC), as well as other nature-based options like afforestation and reforestation, oceanic fertilisation, sustainable building materials, enhanced weathering and soil sequestration, to achieve ambitious carbon reduction targets.

6.2 DACCS and DACCU

The development of direct air capture (DAC) technology dates back to the 1990s, when the technology was used to capture exhaled CO_2 on board space stations and submarines to extend missions underwater or in space. Since then it has found new uses in removing CO_2 directly from the atmosphere (Geoengineering Monitor, 2019).

Direct air (carbon) capture and utilisation (DACCU) and direct air (carbon) capture and storage (DACCS) are variants of carbon capture technology used for the separation of CO_2 from ambient air, instead of from the flue gases of the industrial process. Three pathways are used for capturing CO_2 from ambient air: chemicals (using either liquid or solid sorbents), cryogenic and membranes. Current commercial, pilot and demonstration projects use chemical separation for removing CO_2. Chemical sorbents work either by absorption, where CO_2 dissolves into the sorbent, or adsorption, where CO_2 molecules stick to the solvent surface. However, the absorption model requires high-grade heat that is usually supplied by fossil fuels for the regeneration of the solvent, which serves to only partially offset emissions, increasing the cost per tonne of emissions avoided (Fasihi et al., 2019). On the other hand, the adsorption model uses low-temperature aqueous solvents, which can be supplied by heat pumps powered by renewable energy, reducing costs.

The main difference between a capture facility in a power plant or an industry and DAC is the concentration of CO_2 in the input stream. The concentration in the former varies depending on the process, ranging anywhere from 20–30% in iron and steel facilities to 98–99% in ammonia plants (Bains et al., 2017). The concentration of CO_2 in the air is roughly 400 parts per million by volume, which is 100–300 times more dilute than flue gases from gas and coal-fired plants. For this, a higher surface area of solvent in contact with input stream is needed. Additionally, more fan power is required, making it a dominant cost compared to just 3% in industrial CCS; but this can be supplied from renewables (Bui et al., 2018).

Significant energy requirements are imposed by DACCS/DACCU. Current specific energy required for capturing 1 tCO_2 stands at 0.14–0.23 tonne of oil equivalent (toe) (IEA, 2020). This translates into 1 628–2 258 kWh/tCO_2 captured. Therefore, to capture 1 Gt of CO_2, we would need approximately 1–1.6% of 2018 global total energy supply.

In addition to energy requirements, water and materials requirements to remove CO_2 pose a significant challenge (NASEM, 2019).

DAC comes with advantages too. It benefits from the flexibility of its location, as CO_2 is equally concentrated in the air around the world. This can eliminate land requirements when competing with other land uses.

Several companies operate in the field of DACCU and DACCS, mostly using low-temperature absorption solvent for capture. There are two currently operating plants capturing over 9.3 ktpa CO_2 and one plant under development. In addition, there have been 15 pilot and demonstration projects – three completed, seven operating and five at different stages of development. Out of these, Climeworks has operated plants in Europe and the United States and sells CO_2 based on a subscription model (Friedmann, 2021); and OXY and Carbon Engineering's DAC projects aim to temporarily store captured CO_2 in EOR. The CO_2 captured, though dilute for geological storage (50% vol), is however usually used for concrete, algae farms, packaged foods and beverage production (Bains et al., 2017). Plans for such plants are constantly evolving and often the status is commercially sensitive and not publicly available. This list (Figure 43) is not definitive, therefore, but is indicative of the current status and near-term potential.

Costs

The costs (Table 12) of DAC vary in the literature, as the technology has not yet been demonstrated on a large scale. The most frequently quoted estimate is USD 600–800/tCO_2 avoided by the American Physical Society (Socolow et al., 2011). Newer studies have estimated lower costs. Carbon Engineering has estimated costs in the range of USD 94–232/tCO_2 avoided but these numbers are only theoretical and will need to be demonstrated (Keith et al., 2018). The technology is still comparably more expensive but using it may reduce other costs such as transportation.

FIGURE 43: Non-exhaustive list of direct air capture projects

● Pilot and demonstration ● Commercial ● Laboratory

Facility	Location	Capacity Mtpa/CO_2	Status: Early development	Under construction	Operating	Completed	NA
Climeworks CELBICON	IT	0				●	
Climeworks DAC-3	IT	0.00015				●	
Climeworks Hinwil	CH	0.0009			●		
Climeworks ORCA	IS	0.004			●		
CORAL	DE	0			●		
Herøya	NO	0.021	●				
Huntsville	USA	0.004			●		
Infinitree	USA	-					●
Kopernikus Project P2X	DE	-				●	
Móstoles	ES	-	●				
OXY and Carbon Engineering	USA	1	●				
Palm Spring Demo	USA	-	●				
Rapperswil	CA	-				●	
Skytree	NL	-					●
Soletair	FI	-			●		
Squamish demonstration	CA	0.000365			●		
SRI International, Menlo Park	USA	0			●		
Synhelion	CH	-			●		
Wallumbila - APA Renewable Methane Demonstration Project	AU	-		●			
Zenid	NL	-	●				

AU - Australia, CA - Canada, CH - Switzerland, DE - Germany, ES - Spain, FI - Finland, IT - Italy, IS - Iceland, NL - Netherlands, NO - Norway, USA - United States.
Source: Based on Geoengineering Monitor (2019, 2021); NASEM (2019); Viebahn, Scholz and Zelt (2019).

TABLE 12: Capital and CO_2 avoidance costs for DAC from literature

<table>
<tr><th>Technology</th><th>Capacity (tpa CO_2)</th><th>Capex (USD/t)</th><th>Avoided cost of capture (USD/tCO_2)[28]</th></tr>
<tr><td rowspan="7">HT aqueous solution</td><td rowspan="6">1 000 000</td><td>1 788–2 357</td><td>349–439</td></tr>
<tr><td>1 166</td><td>226</td></tr>
<tr><td>807</td><td>178</td></tr>
<tr><td>706</td><td>157</td></tr>
<tr><td>620</td><td>133.4</td></tr>
<tr><td>920</td><td>1 040</td></tr>
<tr><td>NA</td><td>870</td><td>130</td></tr>
<tr><td rowspan="4">LT solid solution</td><td>360</td><td>1 378</td><td>230–231</td></tr>
<tr><td>360 000</td><td>825</td><td>152–200</td></tr>
<tr><td>360 000</td><td>825</td><td>135–175</td></tr>
<tr><td>NA</td><td>1 423</td><td>215</td></tr>
</table>

Source: Based on Fasihi et al. (2019); Socolow et al. (2011); Keith et al. (2018); Roestenberg (2015).

28 Consists of costs for capturing the carbon and does not include transport or storage costs.

REFERENCES

Agbor, E. et al. (2016), "Integrated Techno-economic and Environmental Assessments of Sixty Scenarios for Co-firing Biomass with Coal and Natural Gas", *Applied Energy*, Vol. 169, pp. 433–449.

AkerSolutions (2019), "Aker Solutions' Carbon Capture and Storage Technology Gets DNV GL Approval", www.akersolutions.com/globalassets/investors/presentations/aker-solutions-carbon-capture-nov-2019.pdf, (accessed February 1, 2021).

Australian Government (2021), "National Inventory Report 2019, The Australian Government Submission to the United Nations Framework Convention on Climate Change*", Australian National Greenhouse Accounts, Volume 1*, Department of Industry, Science, Energy and Resources, Canberra, www.industry.gov.au/sites/default/files/April%202021/document/national-inventory-report-2019-volume-1.pdf.

Babin, A., C. Vaneeckhaute and M.C. Iliuta (2021), "Potential and challenges of bioenergy with carbon capture and storage as a carbon-negative energy source: A review", *Biomass and Bioenergy*, Vol. 146, 105968, https://doi.org/10.1016/j.biombioe.2021.105968.

Bains, P., P. Psarras and J. Wilcox (2017), "CO2 capture from the industry sector", *Progress in Energy and Combustion Science*, Vol. 63, pp. 146–172, https://doi.org/10.1016/j.pecs.2017.07.001.

Beagle, E., and E. Belmont (2019), "Comparative life cycle assessment of biomass utilization for electricity generation in the European Union and the United States", *Energy Policy*, Vol. 128, pp. 267–275, https://doi.org/10.1016/j.enpol.2019.01.006.

BECCS Task Force (2018), *Technical Summary of Bioenergy Carbon Capture and Storage (BECCS)*, Carbon Sequestration Leadership Forum (CSLF), Technical Group.

Bhave, A. et al. (2017), "Screening and techno-economic assessment of biomass-based power generation with CCS technologies to meet 2050 CO2 targets", *Applied Energy*, Vol. 190, pp. 481–489, https://doi.org/10.1016/j.apenergy.2016.12.120.

Bioenergy Europe (2019), *Bioenergy Carbon Capture and Storage*, https://bioenergyeurope.org/article/206-bioenergy-explained-bioenergy-carbon-capture-and-storage-beccs.html.

Bui, M. et al. (2018), "Carbon capture and storage (CCS): the way forward", *Energy & Environmental Science*, Vol. 11, pp. 1062–1176, https://doi.org/10.1039/C7EE02342A.

Burnard, K. (2019), "CCS in Energy and Climate Scenarios", *IEAGHG Technical Report*, https://ieaghg.org/ccs-resources/blog/new-ieaghg-technical-report-2019-05-ccs-in-energy-and-climate-scenarios, (accessed 24 January 2020).

Calix (2020), "Final project agreements executed for LEILAC-2 CO_2 capture facility", www.calix.global/reduce-co2-emission/final-project-agreements-executed-for-leilac-2-co2-capture-facility/#:~:text=The%20LEILAC%2D2%20key%20objectives%20are%3A&text=Construction%20of%20a%20demonstration%20 plant,other%20than%20compressing%20the%20CO2.

Cebrucean, D., V. Cebrucean and I. Ionel. (2014), "CO_2 Capture and Storage from Fossil Fuel Power Plants", *Energy Procedia*, Vol. 63, pp. 18–26, https://doi.org/10.1016/j.egypro.2014.11.003.

CemNet (2019), "Carbon capture is a loss-maker for Anhui Conch", www.cemnet.com/News/story/167315/carbon-capture-is-a-loss-maker-for-anhui-conch.html, (accessed 1 February 2021).

CLEANKER (2018), "EU research project CLEANKER Technology, progress and project perspectives", presented at the ECRA/CEMCAP/CLEANKER Workshop "Carbon Capture Technologies in the Cement Industry", Belgium, www.sintef.no/globalassets/project/cemcap/presentasjoner/17-oct-2018/4_eu_research_project_ cleanker_technology_progressproject-perspectives_m.fantini.pdf.

Consoli, C. (2019), *Bioenergy and Carbon Capure and Storage*, Global CCS Institute, Melbourne, www.globalccsinstitute.com/resources/publications-reports-research/bioenergy-and-carbon-capture-and-storage/.

De Lena, E. et al. (2019), "Techno-economic analysis of calcium looping processes for low CO2 emission cement plants", *International Journal of Greenhouse Gas Control*, Vol. 82, pp. 244–260, https://doi.org/10.1016/j.ijggc.2019.01.005.

Deng, H., et al. (2017), "Leakage risks of geologic CO2 storage and the impacts on the global energy system and climate change mitigation", *Climatic Change*, Vol. 144, pp. 151–163, https://doi.org/10.1007/s10584-017-2035-8.

Drax (2021), "Drax and Mitsubishi Heavy Industries sign pioneering deal to deliver the world's largest carbon capture power project", www.drax.com/press_release/drax-and-mitsubishi-heavy-industries-sign-pioneering-deal-to-deliver-the-worlds-largest-carbon-capture-power-project.

EC (2021), "Cordis EU research results database", European Commission, Brussels, https://cordis.europa.eu/project.

EC (2019a), "Commission publishes 4th list of Projects of Common Interest - making energy infrastructure fit for the energy union", https://ec.europa.eu/info/news/commission-publishes-4th-list-projects-common-interest-making-energy-infrastructure-fit-energy-union-2019-oct-31_en.

EC (2019b), "Candidate PCI projects in cross-border CO2 transport networks in view of preparing the 4th PCI list", https://ec.europa.eu/info/sites/info/files/detailed_information_regarding_the_candidate_projects_in_co2_network_0.pdf.

EC (2019c), *Report from the Commission to the European Parliament and the Council on Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide*, European Commission, Brussels, https://ec.europa.eu/clima/sites/default/files/strategies/progress/docs/com_2019_566_en.pdf.

Hendriks, C. et al. (2013), "Implications of the Reuse of Captured CO2 for European Climate Action Policies", Ecofys and Carbon Counts, prepared for the European Commission, (accessed 22 February 2021).

Emenike, O. et al. (2020), "Initial techno-economic screening of BECCS technologies in power generation for a range of biomass feedstock", *Sustainable Energy Technologies and Assessments*, Vol. 40/100743, https://doi.org/10.1016/j.seta.2020.100743.

Esrafilzadeh, D. et al. (2019), "Room temperature CO2 reduction to solid carbon species on liquid metals featuring atomically thin ceria interfaces", *Nature Communications*, Vol. 10/865, https://doi.org/10.1038/s41467-019-08824-8.

Fajardy, M. et al. (2019), *BECCS deployment: a reality check.*, Imperial College London, www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/briefing-papers/BECCS-deployment---a-reality-check.pdf, (accessed 12 March 2021).

Falkengaard, M.J. and S. Valeur (2021), "Copenhagen energy groups form CCS alliance", *Energy Watch*, https://energywatch.eu/EnergyNews/Cleantech/article12784193.ece.

Fan, Z. and S.J. Friedmann (2021), "Low-carbon production of iron and steel: Technology options, economic assessment, and policy", *Joule*, Vol. 5 (No.4), pp. 829–862, https://doi.org/10.1016/j.joule.2021.02.018.

Fasihi, M., O. Efimova and C. Breyer. (2019), "Techno-economic assessment of CO2 direct air capture plants", *Journal of Cleaner Production*, Vol. 224, pp 957-980.

Freeman, B.C. and A.S. Bhown (2011), "Assessment of the technology readiness of post-combustion CO2 capture technologies", *Energy Procedia*, Vol. 4, pp. 1791–1796, https://doi.org/10.1016/j.egypro.2011.02.055.

Freitas, R.A. (2015), *The Nanofactory Solution to Global Climate Change: Atmospheric Carbon Capture*, IMM Report 45, Palo Alto, CA, USA: Institute for Molecular Manufacturing, www.imm.org/Reports/rep045.pdf.

Fridahl, M. and M. Lehtveer (2018), "Bioenergy with carbon capture and storage (BECCS): Global potential, investment preferences, and deployment barriers", *Energy Research & Social Science*, Vol. 42, 155-165, https://doi.org/10.1016/j.erss.2018.03.019.

Friedmann, J. (2021), "Direct Air Capture is Ready for its Close-up", *Our Daily Planet*, www.ourdailyplanet.com/story/direct-air-capture-is-ready-for-its-close-up/, (accessed 7 March 2021).

Fuss, S. et al. (2018), "Negative emissions—Part 2: Costs, potentials and side effects", *Environment Research Letters*, Vol. 13/063002.

Gabrielli, P., M. Gazzani and M. Mazzoti (2020), "The Role of Carbon Capture and Utilization, Carbon Capture and Storage, and Biomass to Enable a Net-Zero-CO2 Emissions Chemical Industry", *Industrial and Engineering Chemistry Research, American Chemical Society*, Vol. 59/15, pp. 7033–7045, https://doi.org/10.1021/acs. iecr.9b06579.

Gaffney Cline (2020), "Focus on Blue Hydrogen", www.gaffneycline.com/sites/g/files/cozyhq681/files/2020-08/Focus%20on%20Blue%20Hydrogen.pdf.

Gambhir, A. and M. Tavoni (2019), "Direct Air Carbon Capture and Sequestration: How It Works and How It Could Contribute to Climate-Change Mitigation", *One Earth*, Vol. 1, No.4, pp. 405–409, https://doi.org/10.1016/j.oneear.2019.11.006.

Gao, L. et al. (2011), "Cost analysis of CO_2 transportation: Case study in China", *Energy Procedia*, Vol. 4, pp. 5974–5981, https://doi.org/10.1016/j.egypro.2011.02.600.

Garcia Freites, S. and C. Jones (2020), *A Review of the Role of Fossil Fuel-Based Carbon Capture and Storage in the Energy System*, Friends of the Earth Scotland, https://foe.scot/wp-content/uploads/2021/01/CCS_REPORT_FINAL.pdf, (accessed 2 March, 2021).

Geoengineering Monitor (2021), "Direct Air Capture (Technology Briefing)", *Geoengineering Monitor*, www.geoengineeringmonitor.org/2021/02/direct-air-capture-technology-briefing.

Geoengineering Monitor (2019), "Direct Air Capture: Recent Developments and Future Plans", *Geoengineering Monitor*, www.geoengineeringmonitor.org/2019/07/direct-air-capture-recent-developments-and-future-plans/.

Global CCS Institute (2020a), *Global Status of CCS: 2020*, www.globalccsinstitute.com/resources/global-status-report/.

Global CCS Institute (2020b), "*Carbon capture and storage: Challenges, enablers and opportunities for deployment",* Insights and Communications, (accessed 7 October 2021).

Global CCS Institute (2015), *Submission to the European Commission's consultation on revision of the EU Emissions Trading System (EU ETS) Directive*, Global CCS Institute, Melbourne, www.globalccsinstitute.com/archive/hub/publications/189628/global-ccs-institute-submission-european%20commission-consultation-revision-eu-emissions-trading%20system-directive.pdf.

González Plaza, M., S. Martínez and F. Rubiera (2020), "CO2 Capture, Use, and Storage in the Cement Industry: State of the Aret and Expectations", *Energies*, Vol. 13/21, p. 5692, https://doi.org/10.3390/en13215692.

Government of Norway (2020), "The Government Launches 'Longship' for Carbon Capture and Storage in Norway", www.regjeringen.no/en/aktuelt/the-government-launcheslongship- for-carbon-capture-and-storage-in-norway/id2765288/, (accessed February 1, 2021).

Havercroft, I. (2018), *CCS Legal and Regulatory Indicator*, Global CCS Institute, www.globalccsinstitute.com/resources/publications-reports-research/legal-regulatory-indicator-ccs-lri/, (accessed April 2, 2021).

Hepburn, C. et al. (2019), "The technological and economic prospects for CO2 utilization and removal", *Nature*, Vol. 575, https://doi.org/10.1038/s41586-019-1681-6.

Hills, T.P., M.G. Sceats and P.S. Fennell (2019), "Applications of CCS in the Cement Industry", In M. Bui, N. Mac Dowell (Eds.), *Carbon Capture and Storage*, Chapter 10, https://doi.org/10.1039/9781788012744-00315.

Hills, T. et al. (2016), "Carbon Capture in the Cement Industry: Technologies, Progress, and Retrofitting", *Environmental Science & Technology*, Vol. 50/1, pp. 368–377, https://doi.org/10.1021/acs.est.5b03508.

IEA (2020), *Energy Technology Perspectives 2020: Special Report on Carbon Capture Utilisation and Storage*, International Energy Agency, Paris.

IEA (2019), *The Future of Hydrogen*, International Energy Agency, Paris.

IEAGHG (2019a), *Towards Zero Emissions CCS in Power Plants Using Higher Capture Rates of Biomass*, https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/951-2019-02-towards-zero-emissions.

IEAGHG (2019b), *Further Assessment of Emerging CO2 Capture Technologies for the Power Sector and their Potential to Reduce Costs*, https://ieaghg.org/ccs-resources/blog/new-ieaghg-technical-report-2019-09-further-assessment-of-emerging-co2-capture-technologies-for-the-power-sector-and-their-potential-to-reduce-costs.

IEAGHG (2019c), *Sustainability in Petrochemicals, https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/952-2019-01-sustainability-in-petrochemicals.*

IEAGHG (2017a), *Techno-Economic Evaluation of HYCO Plant Integrated to Ammonia / Urea or Methanol Production with CCS, https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/785-2017-02-hyco-plant-with-nh3-or-meoh.*

IEAGHG (2017b), *CO2 capture in natural gas production by adsorption processes for CO_2 storage, EOR and EGR*, https://ieaghg.org/exco_docs/2017-04.pdf.

IEAGHG (2017c), *Techno-Economic Evaluation of SMR Based Standalone (Merchant) Plant with CCS, https://ieaghg.org/exco_docs/2017-02.pdf*.

IEAGHG (2013a), *Iron and Steel CCS Study (Techno-economics of Integrated Steel Mills), https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/1001-2013-04-iron-and-steel-ccs-study-techno-economics-integrated-steel-mill*.

IEAGHG (2013b), *Deployment of CCS in cement industry*, https://ieaghg.org/docs/General_Docs/Reports/2013-19.pdf.

IEAGHG (2013c), *CO2 Pipeline Infrastructure*, https://ieaghg.org/docs/General_Docs/Reports/2013-18.pdf.

IEA/NEA (2020), *Projected Costs of Generating Electricity 2020*, International Energy Agency; Nuclear Energy Agency, https://iea.blob.core.windows.net/assets/ae17da3d-e8a5-4163-a3ec-2e6fb0b5677d/Projected- Costs-of-Generating-Electricity-2020.pdf.

IPCC (2005a), "Underground geological storage", In B. Metz et al. (Eds.), *Carbon dioxide capture and storage,* Chapter 5, Intergovernmental Panel on Climate Change, Switzerland, www.ipcc.ch/report/carbon-dioxide-capture-and-storage/.

IPCC (2005b), "Transport of CO2", In B. Metz et al. (Eds.), *Carbon dioxide capture and storage*, Chapter 4, Intergovernmental Panel on Climate Change, Switzerland, www.ipcc.ch/report/carbon-dioxide-capture-and-storage/.

IPCC (2005c), "Mineral carbonation and industrial uses of carbon dioxide", In B. Metz et al. (Eds.), *Carbon dioxide capture and storage,* Chapter 8, Intergovernmental Panel on Climate Change, Switzerland, www.ipcc.ch/report/carbon-dioxide-capture-and-storage/.

IRENA (2021a), *World Energy Transitions Outlook: 1.5°C Pathway*, International Renewable Energy Agency, Abu Dhabi

IRENA (2021b), *Renewable Power Generation Costs in 2020*, International Renewable Energy Agency, Abu Dhabi

IRENA (2020), *Reaching zero with renewables: Eliminating CO2 emissions from industry and transport in line with the 1.5°C climate goal,* International Renewable Energy Agency, Abu Dhabi.

IRENA and Methanol Institute (2021), *Innovation Outlook: Renewable Methanol,* International Renewable Energy Agency, Abu Dhabi.

Irlam, L. (2017), *Global costs for carbon capture and storage*, Global CCS Institute.

Jackson, S. and E. Brodal (2019), "Optimization of the Energy Consumption of a Carbon Capture and Sequestration Related Carbon Dioxide Compression Process", *Energies*, Vol. 12/9, p. 1603, https://doi.org/10.3390/en12091603.

Keith, D.W. et al. (2018), "A process for capturing CO2 from the atmosphere", *Joule*, Vol. 2, No. 8, pp. 1573–1594, https://doi.org/10.1016/j.joule.2018.05.006.

Kemper, J. (2017), *Biomass with carbon capture and storage (BECCS/Bio-CCS)*, IEAGHG, Presentation 10 March, Imperial College, London.

Khorshidi, Z. et al. (2016), "Techno-economic evaluation of co-firing biomass gas with natural gas in existing NGCC plants with and without CO2 capture", *International Journal of Greenhouse Gas Control*, Vol. 49, pp. 343– 363, https://doi.org/10.1016/j.ijggc.2016.03.007.

Kiani, A., K. Jiang and P. Feron (2020), "Techno-Economic Assessment for CO2 Capture From Air Using a Conventional Liquid-Based Absorption Process", https://doi.org/10.3389/fenrg.2020.00092.

Mandova, H. et al. (2019), "Achieving carbon-neutral iron and steelmaking in Europe through the deployment of bioenergy with carbon capture and storage", *Journal of Cleaner Production*, Vol. 218, pp. 118–129.

Mandova, H. et al. (2018), "Possibilities for CO2 emission reduction using biomass in European integrated steel plants", *Biomass and Bioenergy*, Vol. 115, pp. 231–243, https://doi.org/10.1016/j.biombioe.2018.04.021.

Mantripragada, H.C. and E.S. Rubin (2014), "Calcium Looping Cycle for CO2 Capture: Performance, Cost and Feasibility Analysis", *Energy Procedia*, Vol. 63, pp. 2199–2206, https://doi.org/10.1016/j.egypro.2014.11.239.

McQueen, N. et al. (2019), "CCS in the Iron and Steel Industry", In B. Metz et al. (Eds.), *Carbon dioxide capture and storage*, Chapter 11, pp. 353–391, Intergovernmental Panel on Climate Change, Switzerland, https://pubs.rsc.org/en/content/chapter/bk9781788011457-00353/978-1-78801-145-7.

MIT (2016), "Carbon Capture and Sequestration Project Database", Massachusetts Institute of Technology https://sequestration.mit.edu/tools/projects/, (accessed March 17, 2021).

Mousa, E. et al. (2016), "Biomass applications in iron and steel industry: An overview of challenges and opportunities", *Renewable and Sustainable Energy Reviews*, Vol. 65, pp. 1247–1266, https://doi.org/10.1016/j.rser.2016.07.061.

NASEM (2019), *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, National Academies of Sciences, Engineering and Medicine, The National Academies Press, Washington D.C., www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda.

NETL (2019), *Cost and Performance Baseline for Fossil Energy Plants. Volume 1: Bituminous Coal and Natural Gas to Electricity*, National Energy Technology Laboratory, US Department of Energy, www.netl.doe.gov/projects/files/CostAndPerformanceBaselineForFossilEnergyPlantsVol1BitumCoalAndNGtoElectBBRRev4-1_092419.pdf.

OGCI (2020), "CO2 Storage Resource Catalogue", Oil and Gas Climate Initiative, London, www.ogci.com/co2-storage-resource-catalogue/.

Parsons Brinckerhoff and Global CCS Institute (2011), *Accelerating the Uptake of CCS: Industrial use of Captured Carbon Dioxide*, Global CCS Institute, Melbourne, www.globalccsinstitute.com/archive/hub/publications/14026/accelerating-uptake-ccs-industrial-use-captured-carbon-dioxide.pdf.

Vaseghi, M.R., A. Amiri and A. Pesaran (2012), *A review of energy efficiency and CO2 emissions in the US cement industry,* IEEE-IAS/PCA 54th Cement Industry Technical Conference, https://doi.org/10.1109/CITCON.2012.6215686.

Roestenberg, T. (2015), *Design Study Report: ANTECY Solar Fuels Development*, ANTECY, www.antecy.com/wpcontent/uploads/2016/05/Design-study-report.pdf.

Roussanaly, S., et al. (2021), "Towards improved cost evaluation of Carbon Capture and Storage from industry", *International Journal of Greenhouse Gas Control*, Vol. 106, 103263, https://doi.org/doi.org/10.1016/j.ijggc.2021.103263.

Sanmugasekar, K., and V. Arvind (2019), *Towards Negative Emissions in Cement Industry*, Delft University of Technology, https://repository.tudelft.nl/islandora/object/uuid%3A4ad209d2-7d84-4f6b-ad2c-015a81637014.

Seboka, Y., M.A. Getahun and Y. Haile-Meskel (2015), *Biomass opportunities for cement production: Opportunities in Ethiopia*, United Nations Development Programme.

Socolow, R. et al. (2011), *Direct Air Capture of CO2 with Chemicals-A Technology Assessment for the APS Panel on Public Affairs*, American Physical Society (APS).

Srivastava, U., S.K. Kawatra and T.C. Eisele (2013), "Production of pig iron by utilizing biomass as a reducing agent" , *International Journal of Mineral Processing*, Vol. 119, pp. 51–57, https://doi.org/10.1016/j.minpro.2012.12.008.

Stavrakas, V., N.-A. Spyridaki and A. Flamos (2018), "Striving towards the Deployment of Bio-Energy with Carbon Capture and Storage (BECCS): A Review of Research Priorities and Assessment Needs", *Sustainability*, Vol. 10, No. 7, 2206; https://doi.org/10.3390/su10072206.

Szczeniak, J., C. Bauer and T. Kober (2020), *DEEDS Industry Database - Dialogue on European Decarbonisation Strategies*, Paul Scherrer Institute, https://deeds.eu/results/industry-database/.

Tamme, E. (2020), *Where does CCS feature in the European Green Deal?,* Global CCS Institute, www.globalccsinstitute.com/news-media/insights/where-does-ccs-feature-in-the-european-green-deal.

Tanzer, S.E., K. Blok and A. Ramirez (2020), "Can bioenergy with carbon capture and storage result in carbon negative steel?", *International Journal of Greenhouse Gas Control*, Vol. 100/103104, https://doi.org/10.1016/j.ijggc.2020.103104.

Thibeau, S. and V. Mucha (2011), "Have We Overestimated Saline Aquifer CO2 Storage Capacity?" *Oil & Gas Science and Technology - Revue d'IFP Enegies nouvelles, Institut Francais du Petrole*, Vol. 66, No. 1, pp. 81–92, https://doi.org/10.2516/ogst/2011004.

Toktarova, A. et al. (2020), "Pathways for Low-Carbon Transition of the Steel Industry - A Swedish Case Study", *Energies*, Vol. 13, No.15, p. 3840, https://doi.org/10.3390/en13153840.

Toshiba-energy (2021), "Toshiba Starts Operation of Large-Scale Carbon Capture Facility", www.toshiba-energy.com/en/info/info2020_1031.htm.

Townsend, A., and A. Gillespie (2020), *Scaling up the CCS Market to deliver net-zero emissions*, Global CCS Institute.

UNFCCC (2021), *Nationally determined contributions under the Paris Agreement*, United Nations Framework Convention on Climate Changem, Bonn, https://unfccc.int/sites/default/files/resource/cma2021_02a02.pdf.

US DOE (n.d.), "Pre-Combustion Carbon Capture Research", Department of Energy, Washington, D.C. www.energy.gov/fe/science-innovation/carbon-capture-and-storage-research/carbon-capture-rd/pre-combustion-carbon.

US EPA (n.d.), *Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2019*, Environmental Protection Agency, Washington, D.C., www.epa.gov/sites/default/files/2021-04/documents/us-ghg-inventory-2021-main-text.pdf?VersionId=wEy8wQuGrWS8Ef_hSLXHy1kYwKs4.ZaU.

Vaughan, N.E. et al. (n.d.), "Evaluating the use of biomass energy with carbon capture and storage in low emission scenarios", *Environment Research Letters*, Vol. 13, No. 4, 044014.

Venton, D. (2016), "Core Concept: Can bioenergy with carbon capture and storage make an impact?" *Proceedings of the National Academy of Sciences*, Vol. 113, No. 47, p. 13260, https://doi.org/10.1073/pnas.1617583113.

Viebahn, P. A. Scholz and O. Zelt (2019), "The Potential Role of Direct Air Capture in the German Energy Research Program - Results of a Multi-Dimensional Analysis", *Energies*, Vol. 12, No. 18, 3443, https://doi.org/10.3390/en12183443.

Volsund, M. et al. (2018), "Retrofitability of CO2 Capture Technologies to Cement Plants", http://dx.doi.org/10.2139/ssrn.3366119.

von Strandmann, P. et al. (2019), "Rapid CO2 mineralisation into calcite at the CarbFix storage site quantified using calcium isotopes", *Nature Communications*, Vol. 10/1983, https://doi.org/10.1038/s41467-019-10003-8.

Wall, T. (2005), "Fundamentals of oxy-fuel combustion", presented at the Inaugural Workshop of the Oxy-fuel Combustion Network, Cottbus, Germany, https://ieaghg.org/docs/oxyfuel/w1/04W1Wall.pdf, (accessed 2 March 2021).

ZEP (2011a), *The Costs of CO2 Transport - Post-demonstration CCS in the EU*, European Technology Platform for Zero Emission Fuel Power Plants, www.globalccsinstitute.com/archive/hub/publications/119811/costs-co2-transport-post-demonstration-ccs-eu.pdf.

ZEP (2011b), *The Costs of CO2 Storage - Post-demonstration CCS in the EU*, https://zeroemissionsplatform.eu/wp-content/uploads/CO2-Storage-Report.pdf.

ZEP and EBTP (2012), *Biomass with CO2 Capture and Storage (Bio-CCS),*(European Technology Platform for Zero Emission Fossil Fuel Power Plants; European Biofuels Technology Platform.

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