The **Making Mission Possible** Series

Carbon Capture, Utilisation & Storage in the Energy Transition:
Vital but Limited

July 2022

Version 1.0

Executive Summary

Energy Transitions Commission

Carbon Capture, Utilisation & Storage in the Energy Transition: Vital but Limited

The Energy Transitions Commission (ETC) is a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by mid-century, in line with the Paris climate objective of limiting global warming to well below 2°C and ideally to 1.5°C.

Our Commissioners come from a range of organisations – energy producers, energy-intensive industries, technology providers, finance players and environmental NGOs – which operate across developed and developing countries and play different roles in the energy transition. This diversity of viewpoints informs our work: our analyses are developed with a systems perspective through extensive exchanges with experts and practitioners. The ETC is chaired by Lord Adair Turner who works with the ETC team, led by Ita Kettleborough (Director) and Faustine Delasalle (Vice-Chair). Our Commissioners are listed on the next page.

Carbon Capture, Utilisation & Storage in the Energy Transition: Vital but Limited was developed by the Commissioners with the support of the ETC Secretariat, provided by SYSTEMIQ. It brings together and builds on past ETC publications, developed in close consultation with hundreds of experts from companies, industry initiatives, international organisations, non-governmental organisations and academia.

The report draws upon analyses carried out by ETC knowledge partners SYSTEMIQ and BloombergNEF, alongside analyses developed by the International Energy Agency, Intergovernmental Panel on Climate Change, Global CCS Institute, Rocky Mountain Institute and the Mission Possible Partnership. We warmly thank our knowledge partners and contributors for their inputs.

This report constitutes a collective view of the Energy Transitions Commission. Members of the ETC endorse the general thrust of the arguments made in this report but should not be taken as agreeing with every finding or recommendation. The institutions with which the Commissioners are affiliated have not been asked to formally endorse the report.

The ETC Commissioners not only agree on the importance of reaching net-zero carbon emissions from the energy and industrial systems by mid-century but also share a broad vision of how the transition can be achieved. The fact that this agreement is possible between leaders from companies and organisations with different perspectives on and interests in the energy system should give decision-makers across the world confidence that it is possible simultaneously to grow the global economy and to limit global warming to well below 2°C, and that many of the key actions to achieve these goals are clear and can be pursued without delay.

Learn more at:
www.energy-transitions.org
www.linkedin.com/company/energy-transitions-commission/
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Our Commissioners

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President - UK, Norway, Central Asia & Eastern Europe – Worley

Mr. Francesco Caio,
Chief Executive Officer – Saipem

Mr. Spencer Dale,
Group Chief Economist – BP

Dr. Ani Dasgupta,
CEO & President – World Resources Institute

Mr. Bradley Davey,
Executive Vice President, Corporate Business Optimization – ArcelorMittal

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Chief Financial Officer – L&G

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Mr. Agustin Delgado,
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Founder and Chairman – Primavera Capital

Ms. Mallika Ishwaran,
Chief Economist – Royal Dutch Shell

Dr. Timothy Jarratt,
Chief of Staff – National Grid

Dr. Thomas Hohne-Sparborth,
Head of Sustainability Research – Lombard Odier

Ms. Zoe Knight,
Managing Director and Group Head of the HSBC Centre of Sustainable Finance – HSBC

Mr. Jules Kortenhorst,
Chief Executive Officer – Rocky Mountain Institute

Mr. Mark Laabs,
Managing Director – Modern Energy

Mr. Richard Lancaster,
Chief Executive Officer – CLP

Mr. Li Zheng,
Executive Vice President – Institute of Climate Change and Sustainable Development, Tsinghua University

Mr. Li Zhenguo,
President – LONGi Solar

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Chief Executive Officer and President – SSAB

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Chief Executive Officer – We Mean Business

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Chief Executive Officer – Sustainable Energy For All

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Vice-Chairman and CEO – ACWA Power

Ms. Nandita Parshad,
Managing Director, Sustainable Infrastructure Group – EBRD

Mr. Sanjiv Paul,
Vice President Safety Health and Sustainability – Tata Steel

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Mr. Andreas Regnell,
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Head of Strategy and Investor Relations – Rio Tinto

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Group Chief Sustainability Officer – Tata Sons Private Limited

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IG Patel Professor of Economics and Government - Grantham Institute – LSE

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Chair – Energy Transitions Commission

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Dr. Zhao Changwen,
Director General Industrial Economy – Development Research Center of the State Council

Ms. Cathy Zoi,
President – EVgo

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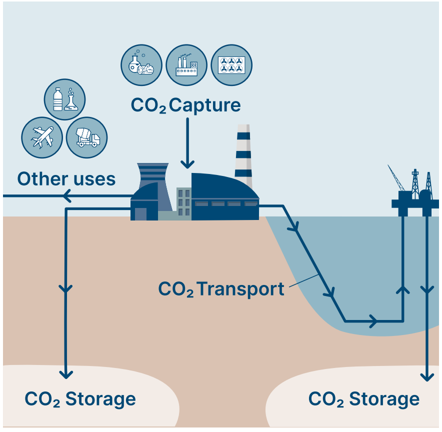
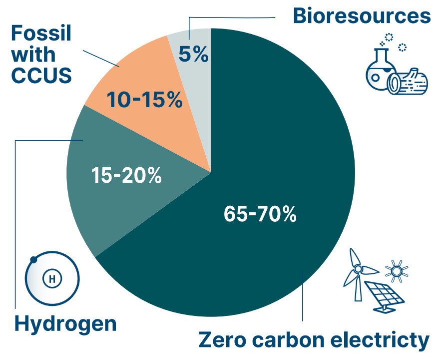
CARBON CAPTURE, STORAGE AND UTILISATION: VITAL BUT LIMITED

CCUS IS CAPTURING CO_2 FOR STORAGE OR USE



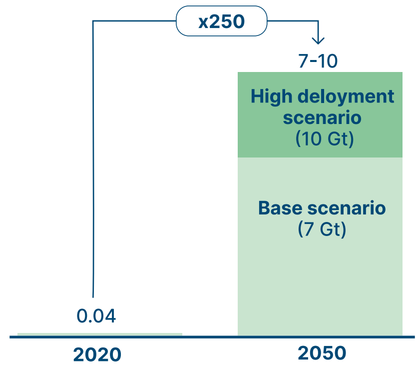
CCUS HAS A VITAL BUT LIMITED ROLE

Final energy mix in a zero-carbon economy by 2050



A SIGNIFICANT SCALE UP IS REQUIRED

Carbon dioxide capture, $GtCO_2$/year



CCUS WILL BE NEEDED IN THREE CONTEXTS

ESSENTIAL ROLE – limited technical alternatives

In industrial processes which produce CO_2 and cannot be decarbonised via other zero-carbon solutions

To provide crucial engineered CO_2 removals from the atmosphere

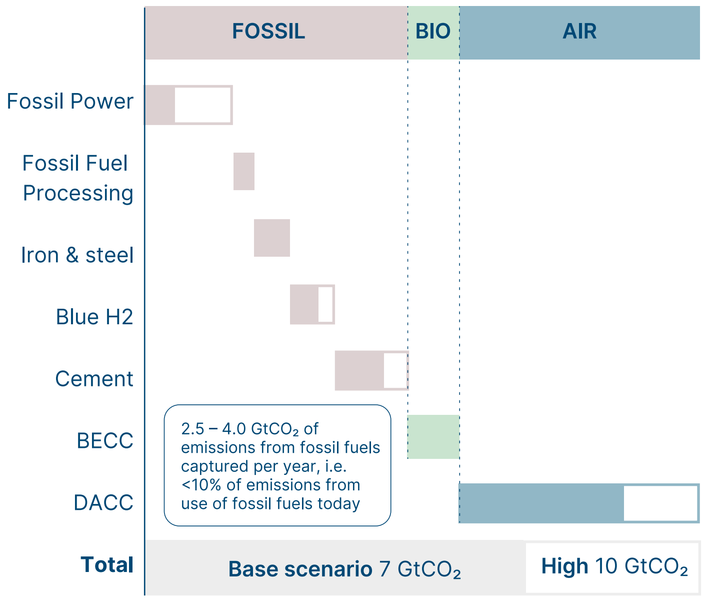
ECONOMIC ROLE

Where it is the lowest-cost decarbonisation solution given local resources and costs

What will it take?

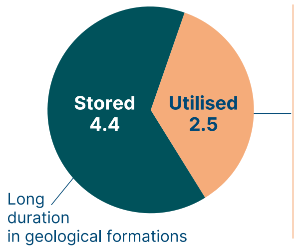
CAPTURING 7-10 $GTCO_2$ PER YEAR

Captured CO_2 by sector, $GtCO_2$/year



MOST CO_2 STORED; SOME UTILISED

CO_2 end of life in 2050, $GtCO_2$/year



HOW IS CO_2 UTILISED?

35% Synthetic Aviation Fuel

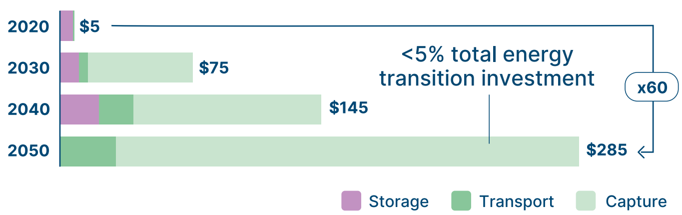
25% High value chemicals & plastics

20% Enhanced oil recovery, under specific and limited conditions

20% Stored in building materials (i.e. cement & concrete)

INVESTMENT MUST REACH \$285bn PER YEAR BY 2050

Annual CAPEX by CCS Segment



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RAPID SCALE UP OF CCUS CAPACITY IN THE 2020S

BY 2030 THE WORLD NEEDS

CO_2 CAPTURE

Annual CO_2 capture up x20, from 40 Mt today to 800 $MtCO_2$

>300 CCUS facilities in commercial operation, from 30 today

Capture in the 2020s will be mainly in Power, Blue Hydrogen & Fossil Fuel Processing

TRANSPORT & STORAGE

1 $GtCO_2$/year storage in operation; another 5Gt under development

~100 CCUS industrial hubs operating around the world

Early storage development is a necessary precondition for CO_2 capture investment

INVESTMENT AND R&D

$70bn/year, up from $3bn/year today

Support innovation via R&D and industrial scale demonstrations

Strong carbon price and de-risking mechanisms are key to unlocking finance

6 KEY ACTIONS BY GOVERNMENTS, INDUSTRY & FINANCE

6 KEY ACTIONS	EXAMPLES	GOVERNMENT	REGULATORS	INDUSTRY	OIL AND GAS FIRMS	FINANCE PLAYERS
Overcoming 'green premium' to make CCUS deployment economic	• Carbon pricing • Mandates for low-carbon end products (e.g. cement) • Public procurement • De-risking mechanisms such as Contracts-for-Difference	✓		✓	✓	✓
Developing key infrastructure	• Shared transport pipelines and storage hubs • Publicly available geological data • Reuse of existing O&G infrastructure • Public funding to bring forward 'injection-ready' storage	✓		✓	✓	✓
Fostering business model and technology innovation	• Targeted R&D support for new capture technologies • New business models such as Carbon Capture as a Service to scale up mature technologies	✓		✓		✓
Regulating and managing risks	• Clear delineation of responsibility for CO_2 at each stage of the value chain • Counterparty risk mitigation through public guarantees, state backed insurance and coordinated hub development	✓	✓	✓		✓
Ensuring high capture rates and storage performance	• Real time monitoring of capture rates • Monitoring Transport and Storage for leakage • Meaningful penalties for non-compliance	✓	✓			
Building public support for an appropriate role for CCUS	• Articulating clear strategic, but limited role • Ensuring transparency on capture and storage performance	✓	✓	✓	✓	

Executive Summary

Global warming poses severe risks to communities and ecosystems this century. To have a 50:50 chance of limiting global heating to 1.5°C, the world must reduce CO_2 emissions to around net-zero by mid-century, with a decline of around 40-50% achieved by 2030. Many countries and companies are therefore now committed to achieving net-zero by mid-century.

The Energy Transitions Commission (ETC) has published several reports demonstrating that it is possible to achieve more rapid reductions in emissions than seemed feasible a decade ago, including in harder-to-abate sectors (Exhibit 1). The IEA's 2021 roadmap Net-zero by 2050 reinforces this message. Massive clean electrification must be at the core of decarbonisation pathways, combined with deployment of a range of complementary technologies, including clean hydrogen and sustainable bioenergy.

However electrification, hydrogen and bioenergy combined cannot reduce gross emissions completely to zero: and even with the most ambitious possible reduction in gross emissions, it is almost certain that cumulative CO_2 emissions between now and 2050 will exceed the "carbon budget" consistent with a 1.5°C climate objective. As described in a recent ETC report, some level of carbon removals will therefore be required alongside deep and rapid cuts in emissions.[1]

Carbon Capture and Utilisation or Storage (CCUS) must therefore play three vital but limited roles in the energy transition:

- To decarbonise those sectors where alternatives are technically limited (i.e. industrial processes which by their nature produce CO_2 such as cement).
- To deliver some of the carbon removals that are required in addition to rapid decarbonisation if global climate objectives are to be achieved.
- And to provide a low-cost decarbonisation solution in some sectors and geographies where CCUS is economically advantaged relative to other decarbonisation vectors locally.

The ETC's recent paper on Carbon Dioxide Removals (CDR) estimated that 70–225 Gt of carbon removals will be required between now and 2050, with an ongoing rate of 3–5 $GtCO_2$ per annum thereafter.[2] Many of these removals can be achieved via "natural climate solutions" such as reforestation, but removals which involve "engineered" approaches to capture and/or to storage will also be required.[3] Note that for the purposes of this report, we treat Direct Air Carbon Capture and Storage (DACCS) and Bioenergy with carbon capture and storage (BECCS) as subcategories of carbon capture and storage technology.[4]

This report therefore assesses the roles which CCUS should play on the path to net-zero and what must happen to ensure it can do so. The key conclusions are that:

- By 2050, the world will likely need to capture and either store, or in some cases use, 7–10 $GtCO_2$ per year of CO_2 through engineered carbon capture solutions.

1 ETC (2022) *Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive*.
2 ETC (2022) *Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive*.
3 Carbon dioxide removals may also be necessary to generate sufficient net negative emissions in the second half of the 21st century to reverse climate-warming effects of an overshoot in the cumulative budget. See chapter 2 of ETC (2022) *Mind the Gap*.
4 CCUS is sometimes associated only with the capture of emissions from fossil fuel or industrial 'point sources'. However for the purposes of this report, we include all technologies that capture and store carbon. This includes Direct Air Carbon Capture (DACC) and Bioenergy with carbon capture (BECC) which are forms of carbon dioxide removal using technological solutions to capture carbon dioxide and to store/utilize for long duration. We therefore treat these as sub-categories of the broader category of CCUS.

- Of this, 3–5 $GtCO_2$ per year will be needed to achieve net zero emissions in applications where the use of electricity, hydrogen, or sustainable bioenergy does not provide a complete solution to decarbonisation. This use of CCUS will make it possible to continue to consume 9 million barrels per day of oil (approximately 90% lower than today), and 2700 BCM of gas per year – (over 30% lower than today) while still achieving a zero emission economy. Around 15% (0.5–0.8 $GtCO_2$ per year) of these capture needs are from industrial processes such as cement production which by their nature produce CO_2, and c. 85% captured from the continued use of fossil fuels where alternatives are less available or prohibitively expensive.

- Another 4–5 $GtCO_2$ per year will be needed to achieve engineered carbon removals.

- Provided strong regulations are in place, CCUS can be technically safe and can be achieved at costs which enable it to play an economically valuable role on the path to net-zero.

- The current pace of development of CCUS is far short of what is required. This reflects past confusions about where CCUS is most needed, inadequate investment, and controversies which have generated public opposition.

- A combination of private investment and supporting public policy is required to ensure that CCUS can play its vital but limited role.

In the past, CCUS has been held back by controversy surrounding safety, permanence and appropriate role. Many environmental groups fear that acceptance of a role for CCUS will divert attention from other, more important decarbonization levers; some fear that CCUS used in applications such as "enhanced oil recovery" which could undermine the transition to a zero-carbon economy or prolong fossil fuel reliance; some express fears that CO_2 storage will not be safe or permanent.

It is therefore useful to recognise the key controversies up front and state the ETC's stance: this is set out in Box 1.

This report seeks to define a strategy for CCUS which both recognizes its essential role and ensures that it does not undermine other aspects of the decarbonization strategy. It covers, in turn;

1. The role of CCUS in the energy transition – vital but limited.

2. The technology, economics and safety of capture, transportation and storage.

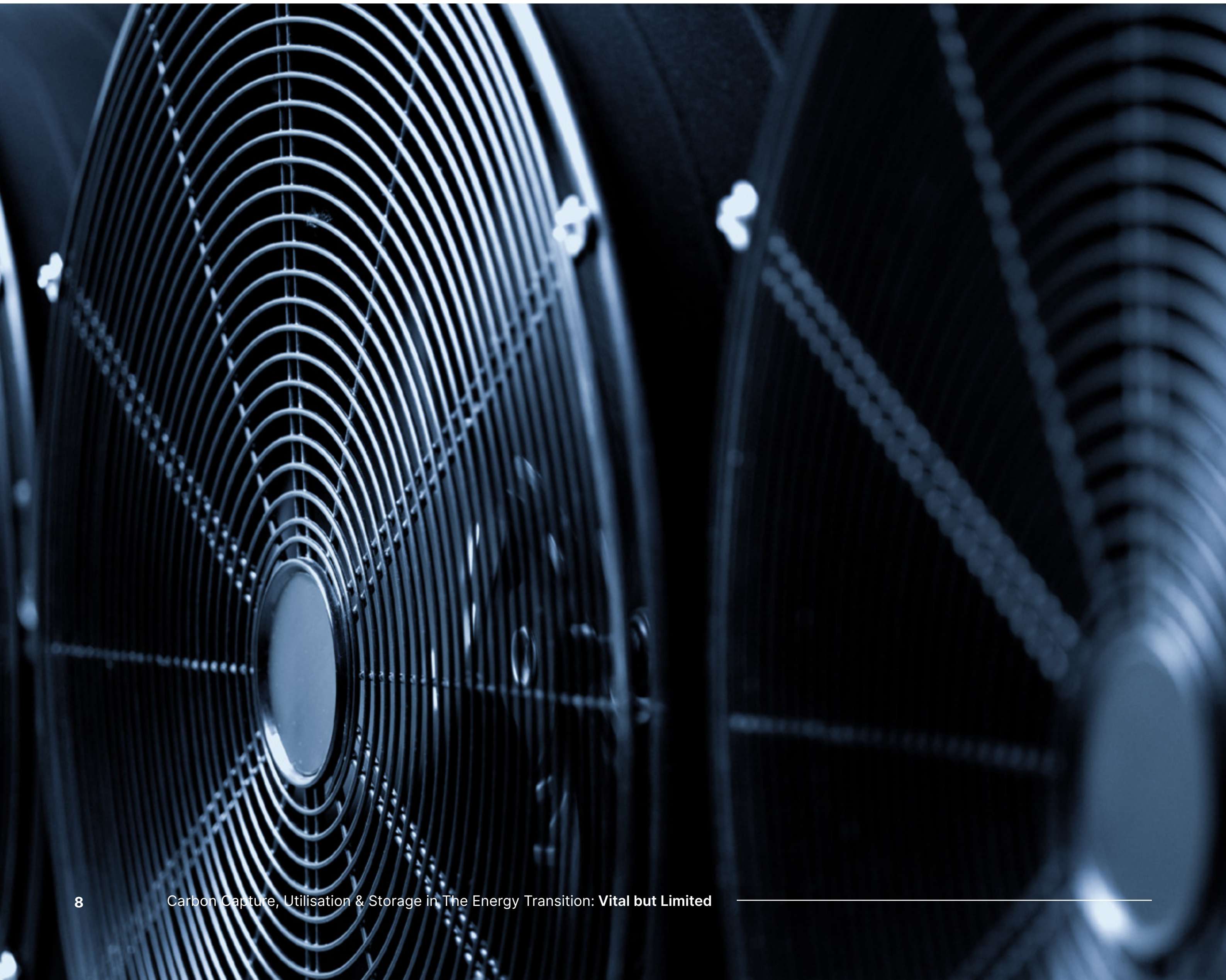
3. Scaling up CCUS in the 2030s and beyond: a plausible pathway.

4. Required action by industry and policy makers.

The ETC's report on CCUS complements previous analyses of decarbonisation and negative emissions technologies

ETC reports on electrification, hydrogen, bioresources and CDR

Exhibit 1



Where does the ETC stand on key controversies surrounding CCUS?

There are widely differing views on the appropriate role of CCUS in meeting decarbonisation objectives. At one end of the spectrum some groups suggest that heavy emitting industries use the promise of future carbon capture technologies as a means to legitimise continued reliance on fossil fuels today (or even indefinitely). Conversely, industry groups complain that a viable and important technology is unfairly demonised due to its association with the fossil sector. The table below sets out the main controversies surrounding CCUS technology and the ETC's stance on each topic.

Moral Hazard: does CCUS risk legitimising business-as-usual?

Some published scenarios have in the past proposed a far larger role for CCUS than appropriate and required, and have therefore seemed to justify a far greater than optimal future role for fossil fuels. But while rejecting that approach, the ETC believes that CCUS will need to play a vital but limited role in the transition to a net-zero economy. Other means of decarbonisation such as electrification, hydrogen, bioenergy and energy productivity improvement will continue to deliver the bulk of emissions abatement, but CCUS will be necessary in some specific sectors and applications.[5] There is now room for greater confidence that CCUS deployment can be targeted to ensure its optimal use to deliver decarbonisation and avoid 'locking in' unnecessary, on-going oil and gas use.

Technology: does CCUS actually work?

CO_2 capture has been demonstrated at scale in many locations. Capture rates over 90% are technically feasible and have been achieved at scale, although early projects often fell well short of this threshold. It is therefore essential to ensure that future projects achieve high capture rates while recognising that even capture rates above 90% mean that CCUS is a very low but not quite zero-carbon technology. Storage in geological formations can be permanent and safe if well-managed, as demonstrated by existing CCUS projects and natural CO_2 stores, but strong regulation will be essential to ensure that this is achieved.

Unrealistic expectations: are the costs and energy requirements for Direct Air Carbon Capture (DACC) implausible?

DACC will always require large energy inputs due to the low concentration of CO_2 in the air. But plausible assumptions on technological progress, renewable energy cost declines, learning by doing and economies of scale, suggests that DACC costs could fall from today's very high levels to below $100 per tonne carbon dioxide ($/tCO_2$) by 2050. Sufficient land, solar and wind resources are available to support at least 3.5 $GtCO_2$ of DACC per annum by 2050.

Enhanced Oil Recovery: does EOR legitimise oil consumption and lower prices?

In the short term EOR may provide a commercially viable model to fund growth in capture/storage technologies.[6] But use of CCUS for EOR has also played a major role in undermining public confidence in CCUS technologies, the role of CCUS in the energy transition and raised 'moral hazard' concerns around legitimising 'BAU' activities.

Public support for CCUS technologies should always strongly favour other critical applications of CCUS (e.g. cement) and on shared transport and storage infrastructure which can underpin multiple applications of CCUS. But if policy support is directed towards EOR this should be strictly limited to situations where:
the combination of CO_2 source and carbon intensity of injection delivers zero or negative net emissions;
captured CO_2 is used, with EOR using mined CO_2 never supported (and ideally discouraged);
overall oil demand is constrained by ambitious decarbonisation policies applied to end use sectors.
Furthermore claims of "carbon neutral" or "zero-carbon" oil should only be made if the net emissions effect is zero or negative.

In total EOR should play only a limited role compatible with future global oil consumption around 7 million barrels per day (Mb/d).

Box 1

5 All the IPCC's latest analysed pathways limiting warming to 1.5°C with no or limited overshoot use CDR to some extent to neutralise emissions from sources for which no mitigation measures have been identified and, in most cases, also to achieve net negative emissions to return global warming to 1.5°C following a peak; IPCC (2022) *6th Assessment Report Working Group 3*.

6 Even in a Net Zero scenario, oil demand does not fall to zero. The ETC estimates 2050 liquids demand at ~9Mbd ("Making Mission Possible: Delivering a Net-Zero Economy", 2020); the IEA estimates 2050 liquids demand at 24Mbd ("Net Zero by 2050: A Roadmap for the Global Energy Sector", 2021).

I. The role of CCUS in the energy transition – vital but limited

- CCUS must play three vital but limited roles in reaching net-zero:
  - To decarbonise those sectors where alternatives are technically limited (i.e. industrial processes which by their nature produce CO_2 such as cement).
  - To deliver some of the carbon removals that are required in addition to rapid decarbonisation if global climate objectives are to be achieved.
  - And to provide a low-cost decarbonisation solution in some sectors and geographies where CCUS is economically advantaged relative to other decarbonisation technologies locally.
- ~7–10 Gt per year of CO_2 capture capacity will be required by 2050 of which around 65% relates to non-fossil fuel sources of CO_2 (e.g. cement process emissions, bioenergy for BECCS and Direct Air Capture).
- The other 35% – around 2.5–4.0 $GtCO_2$ per year – would allow a significant but dramatically reduced scale of fossil fuel use (e.g. around 7 Mb/d and 2,700 billion cubic meters (BCM) of gas, 90% and 30% below today's levels) to be compatible with achieving a zero-carbon economy.

The primary levers of decarbonisation

The vast majority of required emissions reductions can be achieved through levers other than CCUS. As described in three recent ETC reports the 3 vital supply-side technologies are;

Clean electrification, which must play a dominant role.[7]

- Direct use of electricity could grow from today's 20% to over 65% of final energy demand, as electricity is applied to an ever wider share of economic activity (Exhibit 2). This would result in total global direct electricity demand growing from 27,000 TWh per annum today to between 70,000–90,000 TWh.

- And all of this electricity must and can be produced in a zero carbon fashion, with dramatic increases in renewable supply supplemented by hydro, nuclear and other zero carbon power sources. Dramatic falls in the cost of renewables over the last ten years have made this achievable at lower cost than previously believed and therefore imply a lesser role for CCUS in the power sector.

Hydrogen, which will play a major role as a vector of decarbonisation in sectors such as steel, shipping (in the form of ammonia) and chemicals, as well as an energy storage mechanism within power systems. Total hydrogen use could grow from 100 million tons per annum today to somewhere between 500–800 million tonnes by 2050, with the vast majority (e.g. 85% or more) produced in a green fashion from electrolysis of water.[8] This could create demand for another 20,000 to 30,000 TWh of electricity.

Sustainable, low-carbon bioresources which can play a limited but important role, in particular in sectors such as chemicals (as a substitute for fossil feedstocks) and in aviation biofuels. It is essential however that all of the biomass used (whether as a feedstock or as an energy source) is produced in a sustainable fashion. In our Bioresources report, we estimated that total sustainable biomass resources may be limited to 40 to 60 EJ (11,000–17000 TWh) per annum by 2050.[9]

At least 85% of emissions savings will come from these sources. CCUS as a low-carbon, but not zero-carbon technology, should act as a complement not a substitute for these technologies (Exhibit 2).

7 ETC (2021) *Making Clean Electrification Possible*.
8 ETC (2021) *Making the Hydrogen Economy Possible*.
9 ETC (2021) *Bioresources within a Net-Zero Emissions Economy*.

Final energy mix in a zero-carbon economy: electricity will become the dominant energy vector, complemented by hydrogen and fuels derived from it

Final energy mix in a zero-carbon economy – illustrative scenario

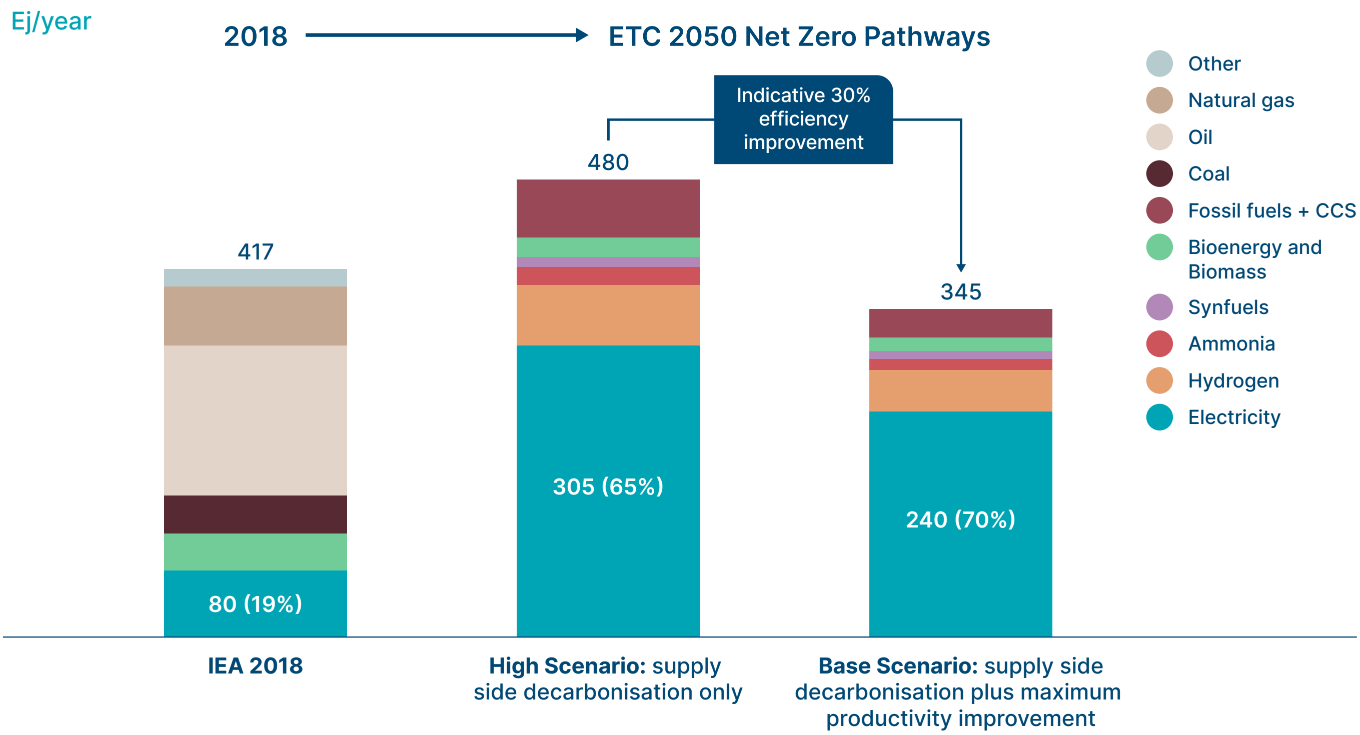


Exhibit 2

SOURCE: SYSTEMIQ analysis for the ETC (2020); IEA (2019) *World Energy Outlook*

However, even with maximum possible energy efficiency improvement, and maximum possible, sustainable use of electricity, hydrogen and bioenergy there will be a necessary role for fossil fuels and a requirement therefore to apply CCUS if emissions are to reach net-zero. In addition, CCUS will be required to offset industrial process emissions (e.g. in cement plants) and to achieve permanent carbon removals.

The role of CCUS – vital but limited

Carbon capture combined with either storage or use will play a vital role in achieving a net zero-carbon economy in four contexts;

- **Carbon removals.** In the ETC's report on Carbon Dioxide Removals we estimate that the world will need to achieve 70–225 Gt of carbon removals over the next 30 years, with an ongoing requirement for 3 to 5 $GtCO_2$ per annum thereafter. Many of these removals will initially be achieved via natural climate solutions, but DACCS and BECCS can and should also play a significant role.

- **Process emissions.** Several industrial processes involve chemical reactions which produce CO_2 whatever the energy source used. Some of these (e.g. the use of coking coal to reduce iron ore to iron) can be eliminated by the development of non-CO_2 emitting processes. But in cement and some chemical sector processes CCUS is almost certain to be required.

- **Constraints on alternative energy supply.** In some sectors, sustainable energy demands may exceed sustainable energy supply. In long-distance aviation, for instance, biofuels may play a key role, but limits to sustainable bioresource supply will likely also require the development of synthetic jet fuel using a captured CO_2 input.

- **Economic advantage**. Even when it is not technically essential, CCUS may be the lowest-cost solution in some applications or regions, at least during transition and in some cases over the long-term.

For the first of these rationales – carbon removals – the need to capture and then store CO_2 is inherent. But both the carbon capture and storage could be achieved in part through nature-based solutions rather than via the engineered capture and storage techniques described in this report, and indeed a portfolio of solutions is likely to be required. Natural climate solutions are currently much lower cost than engineered solutions, but tend to face higher risks to permanence. Developing and investing in a portfolio of different removal types can reduce the overall risk for the planet's CO_2 trajectory. Over time, the balance of costs and risks, which initially favours NCS, will shift to allow a bigger role for engineered solutions. For further discussion of the roles of nature based and engineered solutions see the ETC's recent report on carbon dioxide removals.[10]

The ETC Base scenario sees just under 7 $GtCO_2$ captured per annum by 2050; High deployment sees just over 10 $GtCO_2$

Scenarios for CCUS volumes in 2050 - by source of capture

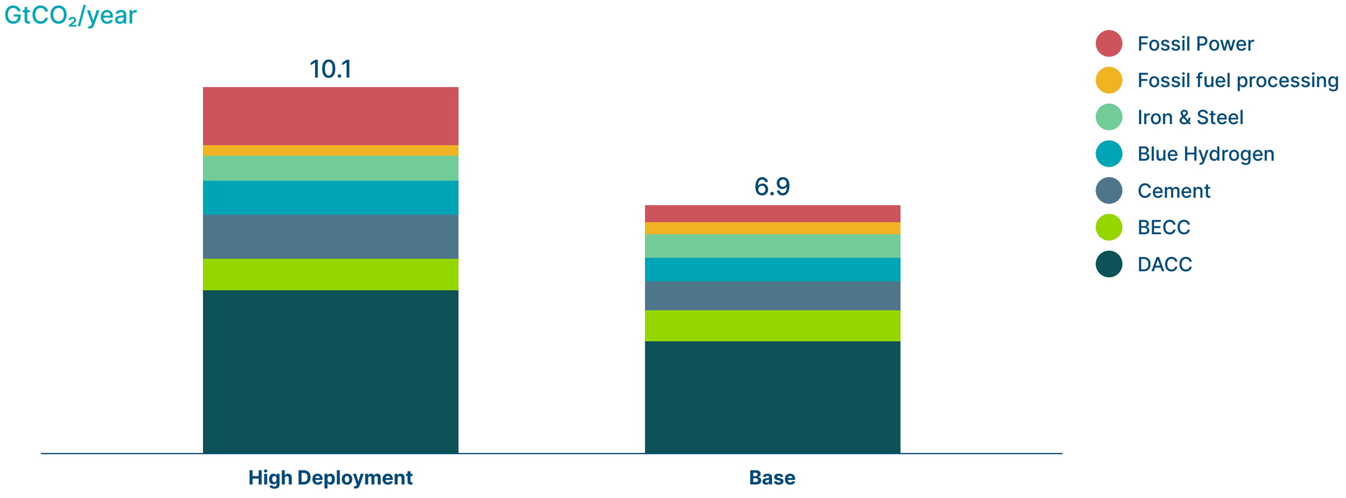


Exhibit 3

NOTES: Fossil Fuel Processing refers to natural gas processing, refinery operations and high value chemicals production. Blue Hydrogen includes ammonia production. BECC = Bioenergy with Carbon Capture. DACC = Direct Air Carbon Capture.

10 Natural climate solutions currently entail lower estimated costs of abatement than the engineered and often provide improved outcomes for biodiversity, water supply, food security. However, NCS assets have inherent risks with respect to accurate estimates of sequestration volumes; permanence of sequestration; of sequestration being reversed e.g., through forest fires. Engineered solutions have much higher costs and fewer co-benefits than NCS. However, the amount of CO_2 sequestered via storage can be defined; Permanence in geological storage is inherently more straight-forward to ensure, provided robust project design, monitoring and verification systems are in place. For further discussion see Chapter 4 of ETC (2022) "Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive".

For the other three rationales, alternative technology options might become possible or become more economic over time. The required and optimal role for CCUS will therefore depend on the evolution of both CCUS and other technologies and costs over time. This report therefore sets out two scenarios for the role of CCUS in 2050: a High Deployment Scenario and Base Scenario, with total capture ranging from 7–10 $GtCO_2$/year, shown in Exhibit 3.

Exhibit 4 illustrates for the Base case (7 $GtCO_2$) the different sources of CO_2 (and thus the applications in which capture is applied), where CO_2 could end up at end-of-life, and the impact of CCUS on CO_2 emissions and atmospheric concentrations.

- **CO_2 capture:** About 3.1 $GtCO_2$ per annum is captured via direct air capture and about 0.9 $GtCO_2$ is first captured via photosynthesis to produce bioenergy and then captured again as part at the end of a BECCS process. The other 2.9 $GtCO_2$ derives from capture in a range of sectors, with hydrogen, cement and iron & steel the most important.

- **End-of-life:** 4.4 $GtCO_2$ ends up being stored in geological formations, while about 2.5 $GtCO_2$ is used in a variety of applications, of which aviation fuels is the most important (ultimately returning emissions to the atmosphere). Enhanced oil recovery, where CO_2 is injected (and then stored) underground to extract oil, accounts for a small 0.5 Gt. The role of carbon utilisation in different sectors, including EOR, is discussed in Chapter 2 Sections 2.4 and 2.5 of the main report.

- **Source:** Of the 6.9 $GtCO_2$ captured, 2.9 $GtCO_2$ comes from fossil combustion or industrial processes, 3.1 $GtCO_2$ direct from the air and 0.9 $GtCO_2$ from biomass.

- **Impact on emissions:** DACC and BECC when combined with permanent storage result in 2.6 Gt of carbon dioxide removals (or so called 'negative emissions'). Where capture occurs following a fossil fuel combustion process or chemical reaction and the CO_2 is permanently stored, the result is net-zero emissions for the industrial. These together amount to 3.1 $GtCO_2$ per annum in 2050. Where capture occurs at the end of a fossil fuel combustion process or chemical reaction and is combined with short-term utilisation, this results in an increase in carbon efficiency ("using the same molecule twice") but does not achieve zero emissions. This amounts to 1.2 $GtCO_2$ per annum in 2050. The details of these different effects are discussed in Section 2.1 of the main report.

Varying combinations of CO_2 capture and end of life imply different impacts on CO_2 emissions

CCUS volumes in 2050 under Base scenario

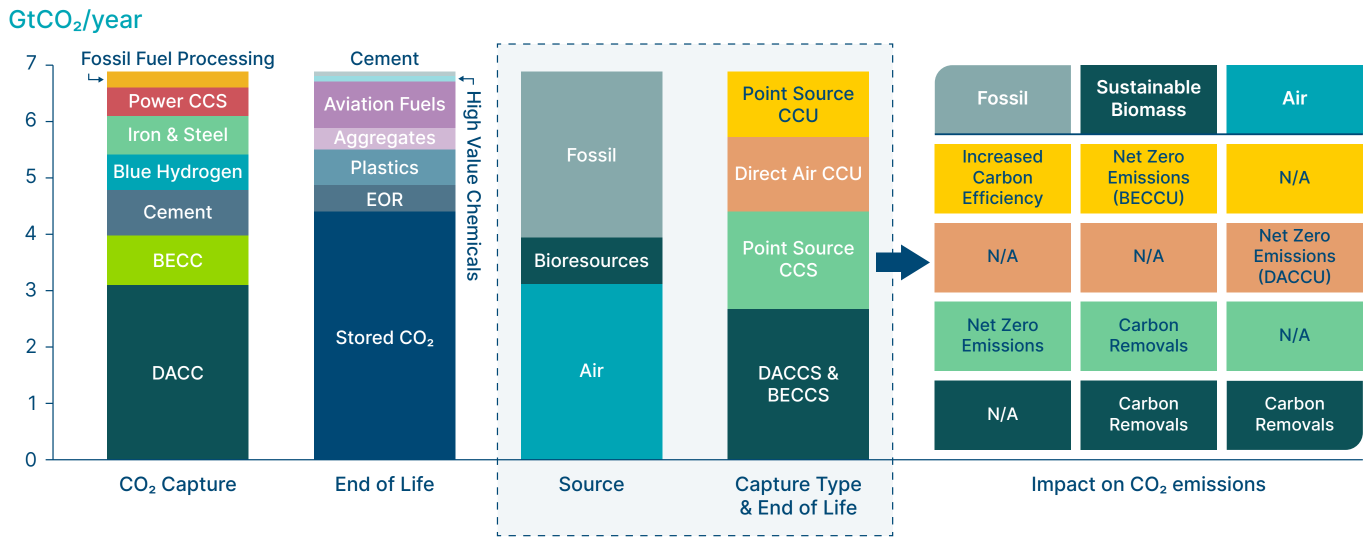


Exhibit 4

NOTES: Volume shown refer to Base Scenario in which demand side measures are fully implemented. Fossil Fuel Processing includes natural gas processing, oil products refining and production of high value petrochemicals (methanol, ethylene, propylene, butadiene, benzene, toluene, xylene). EOR = enhanced oil recovery. CCU = carbon capture and utilization. CCS = carbon capture and storage. DACCS = direct air carbon capture and storage. DACCU = direct air carbon capture and utilization. BECCS = bioenergy with carbon capture and storage. Note that the majority of point source CCS emissions will come from fossil processes and combustion.

SOURCE: SYSTEMIQ for the ETC (2022)

Of the 7–10 $GtCO_2$ per annum captured in our scenarios by 2050, between 3–5 Gt come from the combustion or other use of fossil fuels. Today about 30 $GtCO_2$ per annum of emissions result from fossil fuel use. Therefore 85-90% of the reduction in net fossil fuel emissions will result from reduced use of fossil fuels rather than the capture of emissions produced by continued use. Our scenarios thus imply a reduction of about 90% in coal consumption, 90% in oil and a 30% decline in gas use.

Carbon capture combined with either storage or utilisation will play a vital role across an array of sectors in the economy and for differing reasons:

Carbon Dioxide Removal: Significant emissions removals can be realised through Natural Climate Solutions (NCS) such as tree-planting or various forms of soil carbon sequestration, but engineered removals such as BECCS and DACCS will also be required. NCS solutions are likely to dominate in the 2020s, but BECCS could reach around 0.2 $GtCO_2$ in 2030 and 0.8 $GtCO_2$ in 2050, while direct air capture DACC could grow from a minimal level of 0.1 $GtCO_2$ in 2030, to reach 3.1–4.5 $GtCO_2$ per annum by 2050. The resource implications of this are considered in Chapter 2 of the report.

Cement: Around 60% of the emissions in cement production results from the chemical reaction which separates CO_2 from CaO when limestone is heated, with the other 40% deriving from the combustion of fossil fuels to provide the heat. Whilst the energy input for heat generation could be electrified, or switched from coal to biomass, biogas or hydrogen, process emissions arising from calcination would remain, requiring carbon capture. Our scenarios assume that by 2050 around 85% of cement produced globally will come from facilities fitted with carbon capture technology, with around 0.8–1.2 $GtCO_2$ per annum captured by 2050.

Blue hydrogen: In the ETC's scenarios green hydrogen provides up to 85% of total clean hydrogen in 2050. But blue hydrogen, where carbon capture is added to natural gas reforming plants, is expected to be cheaper in some low cost locations over the medium-term, and offers a route to decarbonising existing 'grey' hydrogen facilities. This results in 0.6–0.9 $GtCO_2$ of total capture needs in 2050.[11]

Iron and steel: Pathways for decarbonising steel production show a promising role for hydrogen DRI combined with electric arc furnaces, which do not require CCUS. However CCUS is still likely to play a role in capturing emissions from any remaining fossil fuelled processes. This represents around 0.7 $GtCO_2$ per annum captured in 2050.[12]

Petrochemicals: Pathways for petrochemicals decarbonisation suggest up to 85% of emissions could be abated through use of clean electrification and bioresources, with CCUS required for the remaining 15%. This results in around 0.1 $GtCO_2$ of capture needs in 2050.[13]

Fossil fuel processing: Most existing CCUS capacity is on fossil fuel processing, particularly in stripping CO_2 from natural gas. Although fossil fuel use will decline substantially in the energy transition, CCUS can help decarbonize supply in the interim and the small remaining volumes in 2050. Our scenarios assume that most remaining fossil fuel processing and refining capacity fits CCUS by 2050, with 0.2 $GtCO_2$ of capture needs in 2050.

Power generation: Wind and solar are both cheaper than fossil power with CCS in most geographies, and will become more so over time. The role of CCS in power is therefore primarily focussed on (i) its application to biomass/fossil fuel plants operating to provide flexible system balance rather than baseload generation (ii) BECCS operations (which may run in baseload operation assuming sustainable supplies of bioresources) to deliver net carbon removals. In some cases where supply chain constraints limit wind and solar buildout or where wind and solar resources are limited by geography, gas combined with CCS may be appropriate as a low carbon form of power generation, in transition and longer term respectively. By 2050, any remaining fossil fuel use in the power sector would need to be abated: this would require between 0.5–1.6 $GtCO_2$ removals in that year.[14]

Synthetic jet fuel: Pathways for aviation decarbonisation suggest a large role for aviation biofuels, though their scale will be limited by the volumes of sustainable biomass available. Synthetic jet fuel, whereby CO_2 captured from DACC is combined with low-carbon hydrogen, can play a complementary role, and utilises ~12% of total captured CO_2 by 2050.[15]

11 ETC (2021) *Making the hydrogen economy possible.*
12 MPP (2021) *Net zero steel sector transition strategy.*
13 ETC (2020) *Making Mission Possible.*
14 ETC (2021) *Making Clean Electrification Possible.*
15 Mission Possible Partnership (2021) *Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation.*

II. The technology, economics and safety of capture, transportation and storage

- The impact of CCUS on emissions depends on the combination of the source of CO_2 and the end-of-life outcome.
- The majority of CCUS costs are in CO_2 capture and typically reflect CO_2 concentration. Cost reductions are likely to be gradual where CO_2 is captured from industrial processes but more dramatic for DACC.
- Resource requirements for 3.1–4.5 $GtCO_2$/year DACC capacity will be large but manageable.
- CO_2 can be transported safely and at low-cost via pipe, truck or ship.
- Large-scale geological CO_2 storage can be safe and permanent, provided it is well managed and strongly regulated.
- CO_2 utilisation plays a secondary role – where available, storage is typically cheaper.
- Enhanced oil recovery should only play a minor role and must only be supported under specific conditions.

Source and end-of-life combinations

The CCUS value chain can be considered in four stages - Source, Capture, Transport, and End-of-life – which can entail either Storage or Use (Exhibit 5). The impact on atmospheric CO_2 concentrations and thus on the climate depend on the source from which the CO_2 is captured and upon the end-of-life outcome.

- The CO_2 can be sourced either be from fossil fuels, from biomaterials which originally capture CO_2 via photosynthesis, from industry processes which generate CO_2 as a result of chemical reactions, or directly from the air.
- The end-of-life outcome can be either storage, long-term utilisation or short-term utilisation.

The CCUS value chain can be split into four distinct stages

The CCUS value chain

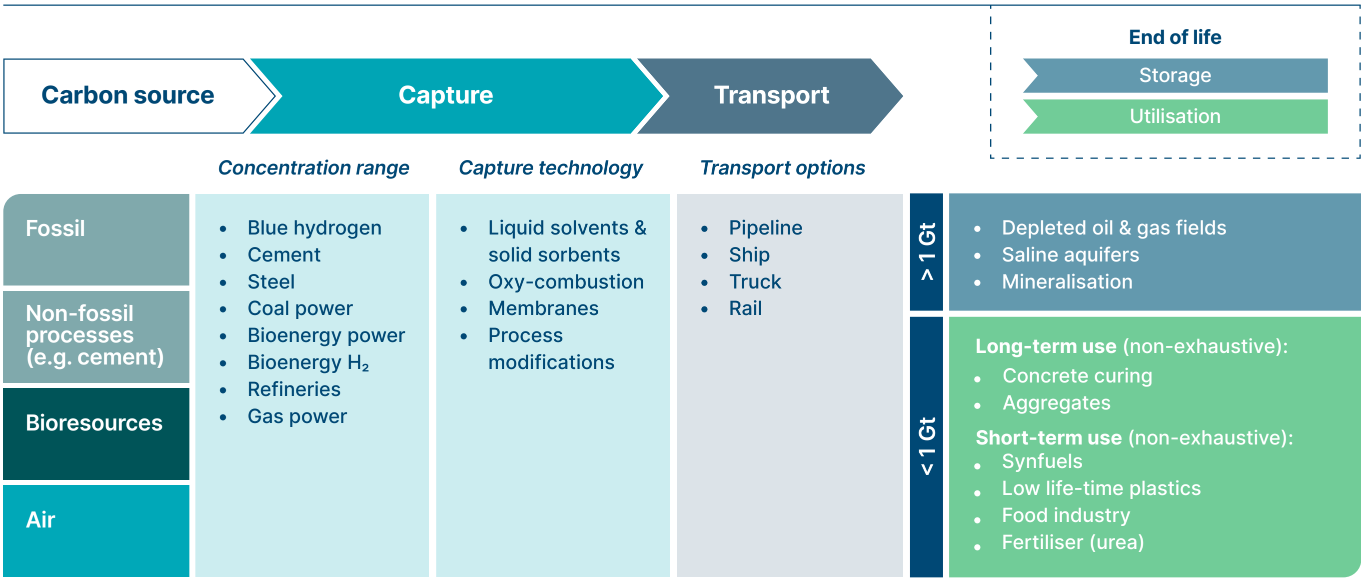


Exhibit 5

SOURCE: SYSTEMIQ for the ETC (2022)

Exhibit 6a shows how different combinations of source and end-of-life outcome result in either net carbon removal, decarbonisation of a sector/application to produce net-zero emissions, or "improved carbon efficiency" in which the same carbon molecule can be used in two or more economic activities before CO_2 is emitted.

Thus for instance;

- The capture of CO_2 from fossil fuel combustion or industrial processes, can result in sector decarbonisation if the CO_2 is stored or is used in long-term applications such as construction aggregates, and it can increase carbon efficiency if CO_2 is used for short-term applications (e.g. to produce a synthetic fuel product). But it will never result in a net carbon removal.

- In contrast, if CO_2 is captured via photosynthesis or via direct air capture, and either stored or permanently used, it can generate net carbon removal (Exhibit 6b).

Any public policies which support CCUS, and all carbon accounting for CCUS, must therefore be based on rigorous assessment of the carbon effect, combining both sources and end-of-life outcomes.

In particular, combinations which result in improved carbon efficiency (e.g. via use to produce transport fuels) are not compatible with achieving a net-zero economy if the input source is fossil fuel combustion or a chemical reaction within an industrial process.

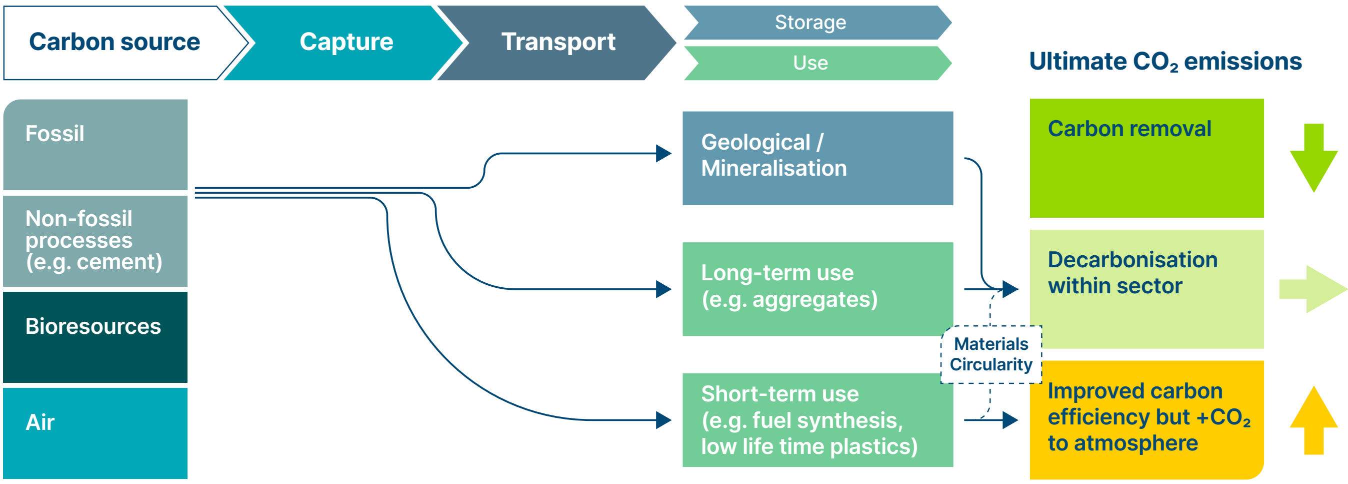
In some short term utilisation applications, CO_2 can in theory be recycled again and again. If the CO_2 is used to produce plastics, it is possible for the plastic to be incinerated at end-of-life with CCUS technology used to re-capture the CO_2. The CO_2 can then be either buried or utilised again. In theory this loop of carbon capture, utilisation incineration and recapture can go on indefinitely, implying atmospheric concentration levels never increase. In practice, all the plastic would need to be recovered and then recycled (either through pyrolysis or via incineration)[16] alongside CCS, presenting a significant challenge. Even if this could be achieved, some leakage would occur since CO_2 capture rates are not 100%. In the scenarios modelled in the report, we assume around half of the CO_2 utilised in plastic production is recycled in this way (see Section 3.1.2).

16 Pyrolysis is a process in which polymers are broken down with extreme heat and reconstituted as virgin petrochemical feedstock. Incineration with CCU captures CO_2 molecules after combustion, allowing potential reuse as plastics.

Exhibit 6a

Emissions captured from fossil combustion and industrial processes can deliver carbon neutrality or improved carbon efficiency

Ultimate emissions of CO_2 from fossil combustion & industrial process

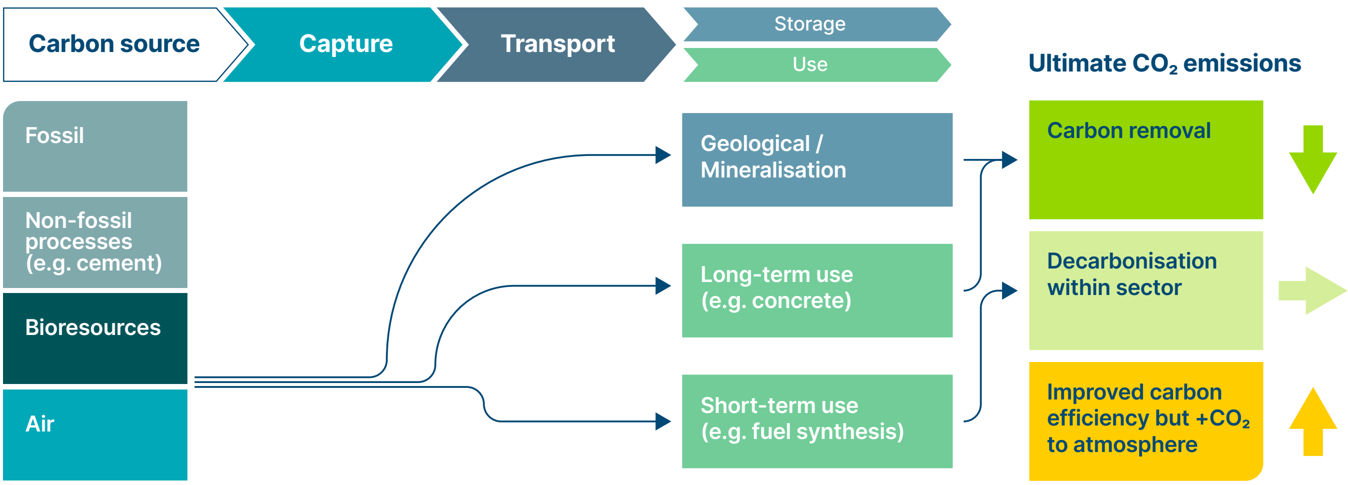


SOURCE: SYSTEMIQ for the ETC (2022)

Exhibit 6b

Emissions captured via DACC & BECC can yield negative emissions

Ultimate emissions of CO_2 from bioresources and DACC



SOURCE: SYSTEMIQ for the ETC (2022)

The CCUS value chain: capture, transport, utilisation and storage

Deployment of CCUS to date has proven that CCUS can be a low-carbon technology, and that transportation and storage can be safe and permanent.

Capturing CO_2 – technological feasibility and cost reduction potential

The majority of CCUS costs are in CO_2 capture (Exhibit 7) and typically reflect the concentration of CO_2 in the body of gases from which the CO_2 is being captured (e.g. high concentration in industrial fossil processes, low concentration if capturing from the air) (Exhibit 8).

Capture rates of around 90% are often treated as a reasonable benchmark of acceptable performance.[17] In practice actual capture rates have frequently fallen short of this threshold, reflecting either cost minimising decisions, engineering failures or an early stage of technological development. Capture rates above 90% are possible, but with progressively higher costs as rates approach 100%.[18] It will therefore often be uneconomic to drive capture rates significantly above 95%. This has three implications:

- CCUS will only be compatible with achieving a zero-carbon economy if residual emissions are clearly recognised and offset by carbon removals.
- Comparisons of the relative cost of different decarbonisation routes (e.g. green versus blue hydrogen) must take into account any residual offset costs.
- It is essential that any public support for CCS is contingent on project developers achieving high capture rates (i.e. at or above ~90%) with support only disbursed when capture has been achieved and accurately measured.

Over the last 10 to 15 years, there has been only limited reduction in carbon capture costs, unlike in solar PV panels, wind turbines, batteries and (more recently) electrolysers, where dramatic cost reductions have been achieved. As a result, the cost competitiveness of other decarbonisation vectors has significantly improved relative to CCUS. Future cost trends for other low-carbon technologies are also expected to be more promising than for CCUS applied to industrial and power generation plants.

In the case of Direct Air Capture however, improvements in energy efficiency and reductions in capex costs driven by learning curve and scale effects are expected to reduce costs from around \$450/tCO_2 today to below \$100/tCO_2 in advantaged regions by 2050 (Exhibit 9).

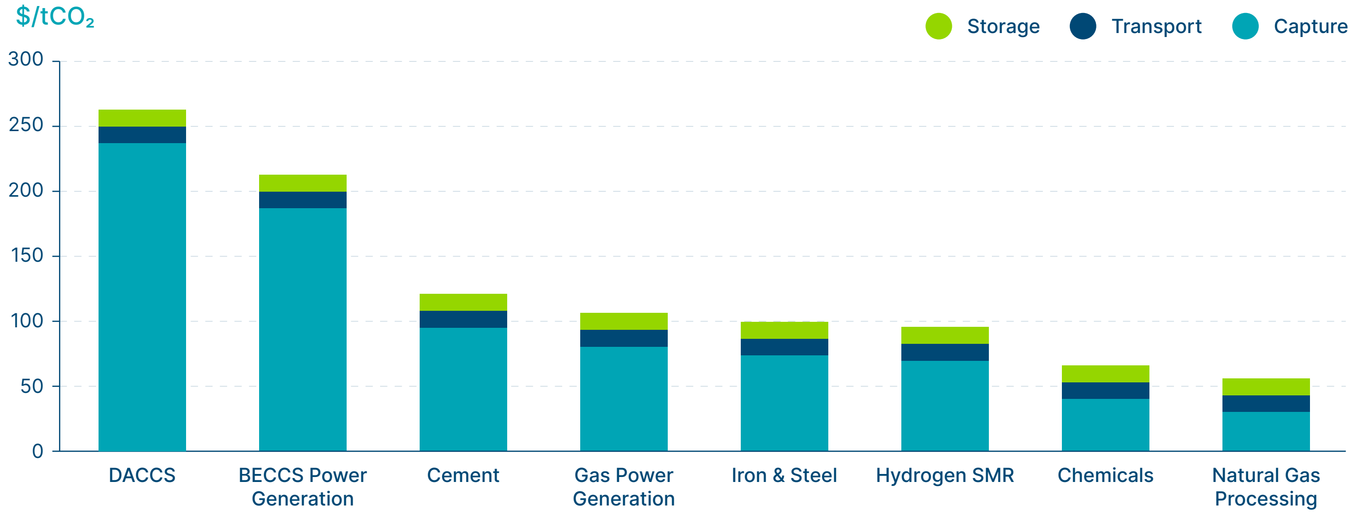
17 IEAGHG (2019) *Towards Zero Emissions CCS in Power Plants Using Higher Capture Rates or Biomass.*

18 Brandl et al, vol. 105 (2021) *Beyond 90% capture: Possible, but at what cost?, International Journal of Greenhouse Gas Control.* Note that some pre-combustion techniques such as the Allam Cycle process capture is inherently 100% and costs do not increase. See Allam et al (2017) *Demonstration of the Allam Cycle: An Update on the Development Status of a High Efficiency Supercritical Carbon Dioxide Power Process Employing Full Carbon Capture.*

Exhibit 7

Cost of capture typically drives the total cost of CCS

Levelised cost of capture, transport and storage by application



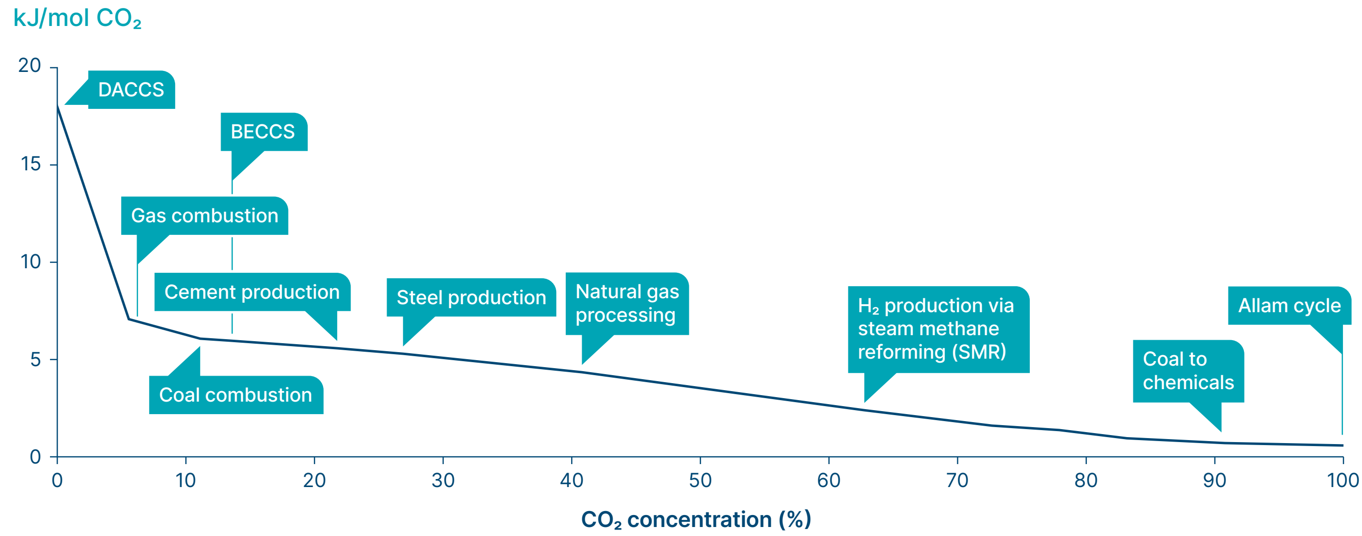
NOTES: CO_2 capture costs for hydrogen refers to production via Steam Methane Reformation (SMR) of natural gas. Cost estimates are based on the United States. All capture costs include cost of compression. Chemicals refers to ethylene oxide. Where a range of capture costs are applicable, the midpoint is shown here.

SOURCE: IEA (2019), *Energy Technology Perspectives – CCUS in clean energy transitions*, GCCSI (2017), *Global costs of carbon capture and storage, 2017 update*, IEAGHG (2014), *CO_2 capture at coal based power and hydrogen plants*, Keith et al. (2018), *A Process for Capturing CO_2 from the Atmosphere*, NETL (2014), *Cost of capturing CO_2 from Industrial sources*, Rubin, E. S., Davison, J. E. and Herzog, H. J (2015), *The cost of CO_2 capture and storage; Fuss et al. (2018) Negative emissions—Part 2: Costs, potentials and side effects*

Exhibit 8

Energy required for CO_2 capture declines with increasing CO_2 concentration

Minimum work required for CO_2 capture



NOTES: SMR = Steam Methane Reforming. The Allam Cycle (see Allam et al. (2017) *Demonstration of the Allam Cycle: An Update on the Development Status of a High Efficiency Supercritical Carbon Dioxide Power Process Employing Full Carbon Capture*).

SOURCE: Bui et al. (2018) *Carbon capture and storage: the way forward*

Declines in the cost of energy as well as improved efficiency and reduced CAPEX requirements drive DACC cost savings

Estimated levelised cost of direct air capture by cost driver and energy costs (RHA) for advantaged regions

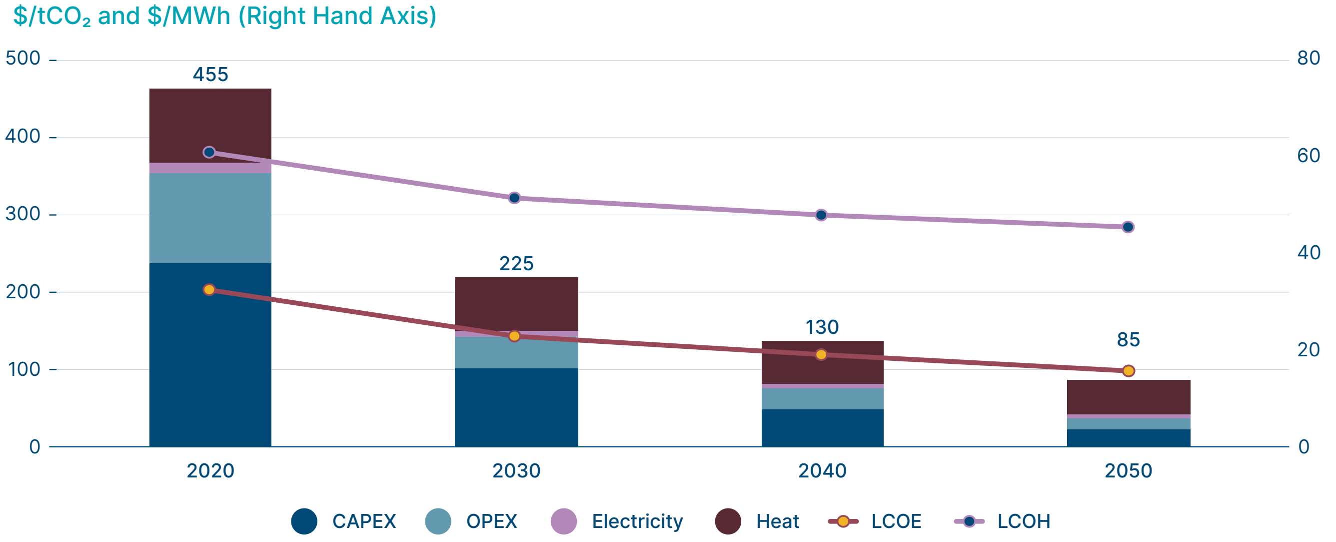


Exhibit 9

NOTES: LCOH/E = levelised cost of heat/electricity; Levelised Cost of CO_2 Direct Air Capture breakdown refers to a fully electrified high temperature DACC system for 5,000 Full Load Hours per annum. Assumes overnight cost of capital for 1MtCO_2 plant in 2020 of $1,470m, weighted average cost of capital of 7% and plant lifetime of 20 years, growing to 30 years by 2050. Capital, heat and electricity costs refer to an advantaged region with abundant wind and solar resources.

SOURCES: SYSTEMIQ for the ETC (2022) based on models developed by Fasihi et al. (2019) *Techno-economic assessment of CO_2 direct air capture plants*; Keith et al. (2018) *A Process for Capturing CO_2 from the Atmosphere*

Resource requirements for DACC

Given the potential for DACC cost reductions, and the need for significant carbon removals, our scenarios suggest a rapid growth of DACC in the late 2030s and 2040s, reaching 3.1–4.5 Gt of CO_2 captured in 2050. Achieving this will require significant energy and other resource inputs, but the scale of these requirements is manageable.

The key requirement is energy in the form of heat and electricity.

- If 3–5 GtCO_2 per annum were captured at today's energy efficiency of ~3 MWh per tonne (~11 Gj/tCO_2), this would imply an additional 9,000 to 15,000 TWh electricity demand, compared to total global electricity production of 27,000 TWh today. This would add significantly to the ETC's estimate of 70,000–90,000 TWh of direct electricity demand in 2050. In addition, green hydrogen (which would be necessary for high temperature liquid solvent DACC) will also require significant electricity inputs.

- If an efficiency improvement to 1 MWh/tCO_2 could be achieved – which some estimates suggest is possible – 3,000–5,000 TWh of electricity would be required: a still very significant, but more manageable figure.

Even electricity requirements at the top end of this range would be manageable in the long term, given the massive scale of global solar and wind resources and the ability to locate DACC plants where renewable electricity is most abundant and land has limited alternative use value. Land area requirements for DACC – whether for the plants themselves or for renewable energy production – are also very small compared to the land requirement to achieve equivalent levels of carbon removal via NCS.

Analysis of requirements for construction materials (such as steel and concrete), for solvent chemicals, and for water do not reveal any significant constraints on the potential scale of deployment.

Transport

CO_2 can be transported safely and at low-cost via pipeline, truck or ship. The majority of transported CO_2 is likely to be transferred via onshore and offshore pipelines.

CO_2 pipelines are a mature technology: an extensive CO_2 pipeline network already exists in North America and the equivalent technology is in use across the world. In the US around 70 $MtCO_2$ is transported via pipeline each year, mainly for the purposes of enhanced oil recovery. International standards concerning materials, safety and leakage rates have been developed, and are in place in some areas today.[19]

The overall need for CO_2 transportation will be determined by the proximity between capture facilities and locations for CO_2 storage or utilisation. However abundant geological storage in most regions of the world (see next section) suggests that in most cases CO_2 will need to be transported for less than 400 km between most capture and storage sites.[20] Sites for utilisation of CO_2 are also expected to be within similar distances of capture sites.

The most cost-efficient mode of transport will depend upon distances involved and quantities of CO_2 being transported. (Exhibit 10). In general, transmission pipelines tend to be the cheapest option if transporting large volumes (Exhibit 11).[21] This is true of both offshore (where pipelines compete with ships) and onshore (where pipelines compete with trucks). Distribution pipelines connecting smaller emitters to trunklines (transmission) will be viable at lower volumes.

Over very long distances ships regain competitiveness as the upfront capital requirement for pipelines becomes too great (Exhibit 12). The IEA estimates shipping becomes competitive with pipelines when distances exceed ~800km (up to 2 $MtCO_2$ per annum being transported), equivalent to the distance between the UK and Norway. Ships may also be cheaper where supply of CO_2 is intermittent, since pipelines require a continuous flow of compressed gas.[22]

Exhibit 10

Pipelines are typically the cheapest means of CO_2 transportation, but other forms of transportation are also low cost

CO_2 transportation options, present day utilisation and optimal scale for 180km and over distance

Transport mode	Today's use	Size	Cost (per tonne/km)
Transmission Pipeline[1]	>8,000 km in operation today, mostly in US	Generally > 1 Mt/year (7 inch or larger)	\$6 (Onshore) \$10 (Offshore)
Ships	Mostly used in food industry	smaller scale (ca. 1,000 tonnes), future scaling up to 50,000 tonnes	\$15
Trucks	Distributed merchant uses (chemical & food industry)	2-30 tonnes/truck	\$22
Rail	-/minimal	~30 – 1000 tonnes	\$13

NOTES: Transport costs are an estimate and indicative as they are likely to vary depending on region, scale, local geology and geographies, labour, monitoring and regulation, and purity prior to transport. [1] Pipeline costs shown refer to trunkline, not distribution.

SOURCE: SYSTEMIQ analysis for ETC (2022); Zero Emissions Platform (2011) *The Costs of CO_2 Transport*; Stolaroff et al. (2021) *Transport cost for carbon removal projects with biomass and CO_2 storage*

19 International Standards Organisation 27913: Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems 2016.
20 IEA (2020) *CCUS in clean energy transition.*
21 Bloomberg NEF (2021) *CCUS Costs and Opportunities for Long Term CO_2 Disposal.*
22 Al Baroudi et al (2021) A review of large-scale CO_2 shipping and marine emissions management for carbon capture, utilisation and storage.

Pipelines become more competitive when transporting large volumes of CO_2

Offshore CO_2 shipping & pipeline costs by volume

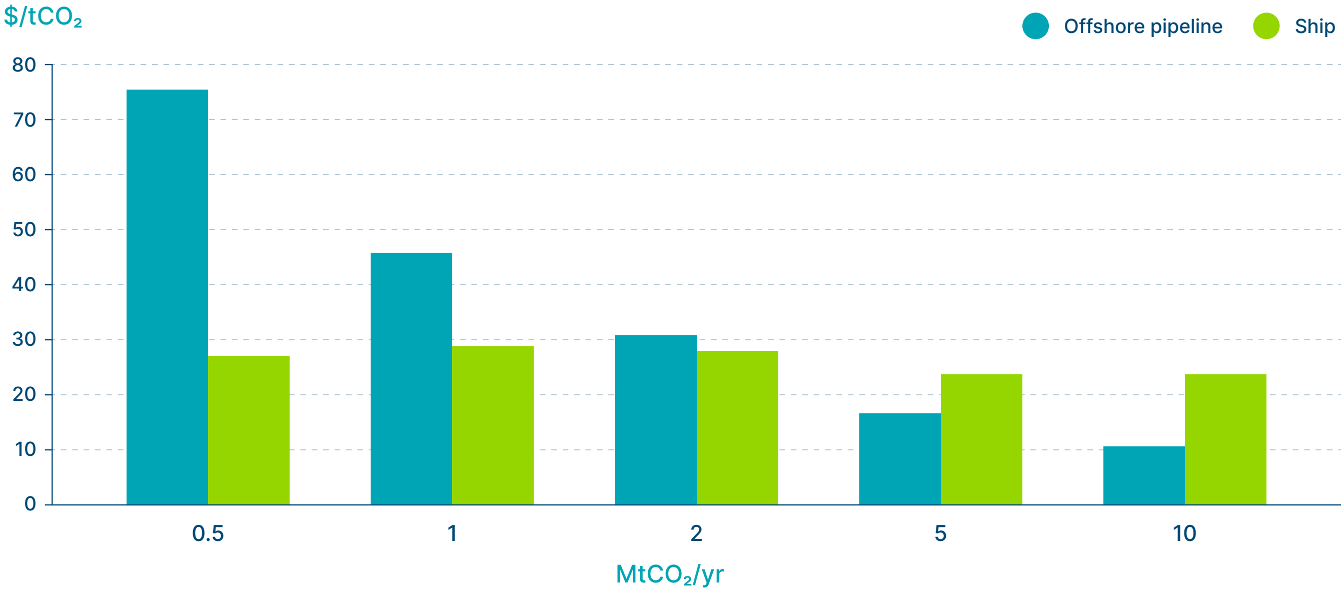


Exhibit 11

NOTE: Assumes distance of 1000km.

SOURCE: IEA (2020) *CCUS in clean energy transitions*

Shipping is cheaper than pipelines over long distances

Cost of CO_2 shipping vs. offshore pipeline

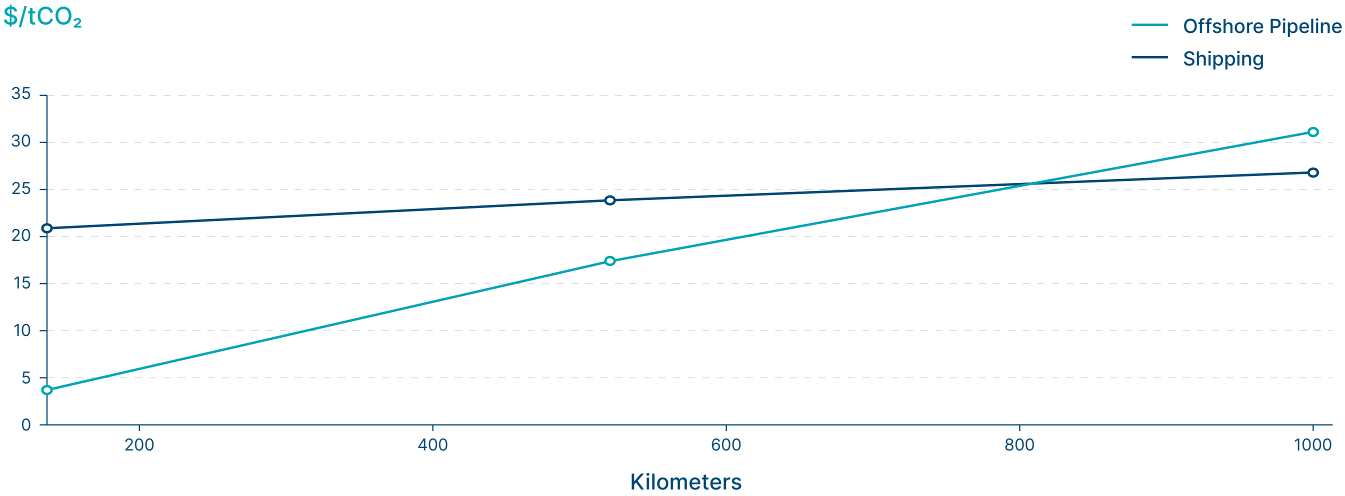


Exhibit 12

NOTES: Assumes a capacity of 2 $MtCO_2$/year.

SOURCE: IEAGHG (2020) *The Status and challenges of CO_2 Shipping Infrastructure*

Use or storage

At end-of-life CO_2 can be permanently stored over periods of 100s or 1000s of years or used in products, materials or fuels. The ultimate carbon balance of capturing, utilising and storing CO_2 will depend on the source of CO_2 and the duration of its storage and/or utilisation. In most cases, storing CO_2 is likely to be cheaper than using it.

Storage: The majority of captured CO_2 is likely to be stored underground in large-scale geological CO_2 stores. Storage can be safe and permanent provided it is well managed and strongly regulated.

- A series of manmade and natural factors act as barriers preventing leakage. Artificial measures include plugging injection wells with steel and concrete seals; natural factors relate to CO_2 being injected under a cap rock which acts as a barrier to release; over time the CO_2 is dissolved in brine or physically absorbed into rock pores.

- Although manmade storage sites have not been in operation long enough to prove their capacity to permanently trap CO_2, naturally-occurring subterranean stores of CO_2 have remained trapped for thousands of years.[23] This is further supported by real world evidence from existing CCS facilities running since the 1990s and from academic studies of the technical feasibility.

- Appropriate monitoring, regulation and assignment of liability will be key to ensuring these estimated values are realised over long periods of time.

Global theoretical geological storage volumes are vast and exist in nearly all regions. Potential storage volumes have been estimated at exceeding 10,000 $GtCO_2$, which would be enough to store today's total annual CO_2 emissions (c. 40 Gt) each year for more than 250 years. A typical site today only injects 0.5–5 $MtCO_2$ per year but larger scale sites of 10–50 $MtCO_2$ per year may become feasible in the future. Of total theoretical volumes, around 85% are in saline aquifers, with 12% in depleted gas fields and 3% in depleted oil fields. There are however two potential constraints on storage development:

- Although storage is available in most geographies, estimates are not always comprehensive. In those locations where local storage is not possible, other CO_2 transportation options such as shipping may be viable, and may be the lowest cost option over long distances.

- Characterising geological storage sites entails demonstrating that sites investigated for storage have sufficient capacity to store the expected CO_2 volumes and sufficient injectivity to receive the expected rate of supplied CO_2. This is an essential step which helps to give confidence in the performance of the reservoir, better estimates of the storage volumes and injectivity, and confidence of the integrity of the site and lack of leakage pathways. However, this step typically takes several years and currently represents a critical bottleneck to further development. This is a potential area where targeted government support (in the form of direct finance or tax breaks for example) can have a meaningful impact. Work should begin in this regard as soon as possible, given that saline aquifers account for the vast majority of CO_2 storage potential but are typically least well understood.

Storage represents a small part of overall CCUS costs, with costs ranging around \$5–20/tCO_2 for storage sites where at least 1 $MtCO_2$ per year is injected (lower volumes per site would tend to lead to higher costs).

Utilisation

Utilisation is likely to play a secondary role to storage but will be important in specific applications. Utilisation refers to all applications in which CO_2 is not stored in a dedicated geological storage site but embedded in a product. Utilising CO_2, rather than storing it, is only a low-carbon option if the utilisation sees the CO_2 effectively stored in materials (e.g. in concrete/aggregates) (Exhibit 13) or if the CO_2 is captured from the air or biomass (rather than from fossil fuel based processes).

- Very long-term utilisation (i.e. more than 50 years) is equivalent to storage and, depending on source, can result in either a net removal or reduction in emissions.

- Short-term storage (i.e. less than 50 years) does not achieve permanent sequestration, since the CO_2 is released to the atmosphere after a relatively short period. If the CO_2 released was originally derived from a biomass or DACC, short-term use enables net-zero emissions economic activity. If the CO_2 is derived from fossil fuel or a chemical reaction, short-term use improves "carbon efficiency" by using the same molecule twice but does not deliver a net-zero emissions result.[24]

23 The IPCC suggests that leakage rates are expected to be low, with expectations that 99% or more of the injected CO_2 will be retained for 1000 years. IPCC (2005), *Special Report on Carbon Dioxide Capture and Storage*.

24 Whilst technically possible, achieving 100% circularity is extremely challenging and would entail additional infrastructure investments. Even with a collection rate of 100%, chemical recycling results in conversion losses which lead to declining overall feedstock levels. This is discussed further in Section 1.2.6 of the main report.

Carbon mineralisation techniques can sequester CO_2 into building materials for very long periods

Duration of CO_2 lock-in by utilisation application

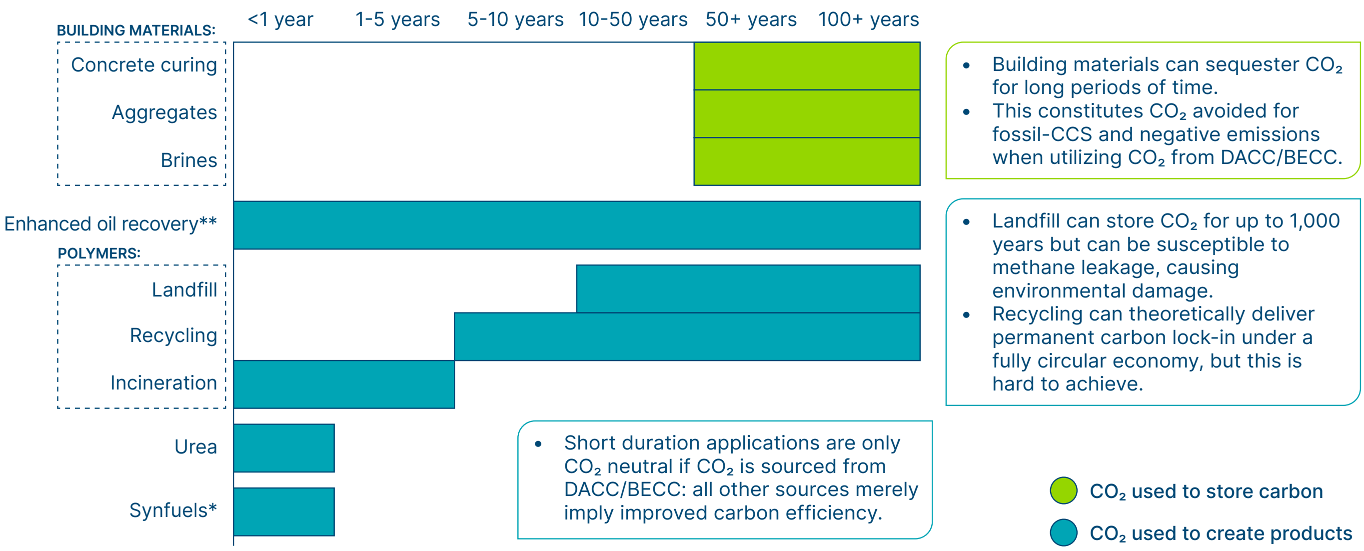


Exhibit 13

NOTES: *Synfuels refers to fuels such as methane, methanol and jet-kerosene. **Duration shown for EOR refers to sequestered CO_2 only, not that which is released immediately upon combustion.
SOURCE: SYSTEMIQ Analysis for the ETC (2021)

The relative merits of utilising CO_2 rather than storing it will depend on the costs and carbon benefits of the utilisation option. Utilisation is typically justified under one of three cases;

- **CO_2 is used as an essential input to a product or process.** In the case of urea and Enhanced Oil Recovery (EOR) the CO_2 input is either essential in a production process which would in any case occur (urea production) or delivers value via increased production (EOR). The cost of utilisation is therefore negative since the urea producers or EOR operators will pay for the CO_2 delivered, even if there is no carbon price. This applies to ~0.5 $GtCO_2$ per year in 2050.

- **CO_2 can be used as an input to a new form of product, but the resulting cost is higher than the existing option.** In the case of synthetic fuel (and also synthetic methane, methanol or plastics) the captured CO_2 is used instead of fossil fuels to produce an economically valuable product, but the total production cost is higher than the conventionally produced product. As a result a carbon price (or equivalent regulation) will be required to make CO_2 sequestration cost competitive with fossil fuel inputs. Assuming that such policies are in place to drive decarbonisation, the crucial question then becomes how this cost of decarbonisation compares with other decarbonisation alternatives. ETC analysis suggests that synthetic fuels, which combine captured CO_2 with low-carbon hydrogen, are likely to become a cost effective option for the decarbonisation of aviation over the next 30 years, utilising around 0.8 $GtCO_2$ per year in 2050. A further 0.7 $GtCO_2$ per year is likely to be required as an input to plastic and chemical production.

- **CO_2 has no economic value, and utilisation is essentially just a form of storage.** In the case of construction aggregates, the CO_2 sequestration is not essential to the economic function or quality of the aggregates delivered, so there is no value to the CO_2. Essentially therefore "using" CO_2 in construction aggregates is effectively another form of storage, and the relevant comparison is between the cost of achieving sequestration within aggregates versus the cost of transport and storage in geological formations (assuming there is a decarbonisation incentive to do both). This "within the value chain" storage may however be a cost competitive solution for a significant share of cement industry emissions, since the distributed location of cement plants will tend to increase CO_2 transport costs to storage sites. Alternatively, utilising CO_2 in the production of aggregates may be cost effective where the process can be harnessed to valorise industrial waste streams. Aggregates are expected to utilise 0.4 $GtCO_2$ per year in 2050 although if the correct industrial residues used in the carbonisation process can be made available, this figure could be an order of magnitude higher. Blending CO_2 into cement could add a further 0.05 $GtCO_2$ per year.

It is particularly important to define whether and in what specific forms Enhance Oil Recovery is a valuable type of CCU. Several oil companies are exploring using direct air capture to sell supposed "carbon neutral oil". But the merits of these claims depend critically on the source of CO_2 and the volume that is injected into the well (Exhibit 14):

- Most CO_2 currently used in in EOR is mined from naturally arising CO_2 sources. In this case and assuming the injection rate is 300 gCO_2 per barrel of oil produced, total life cycle emissions are approximately 500 g/bbl.
- If the CO_2 is derived from an industrial point source process and injected at 300 g/bbl, net emissions also come to 500 g/bbl, but 300 g of these emissions result from a valuable industrial process (implying improved CO_2 efficiency).
- DACC combined with a 300 g per barrel injection rate, can deliver crude oil at 200 g per barrel.
- Only DACC with an injection rate of over 500 g per barrel will deliver zero or negative emissions.

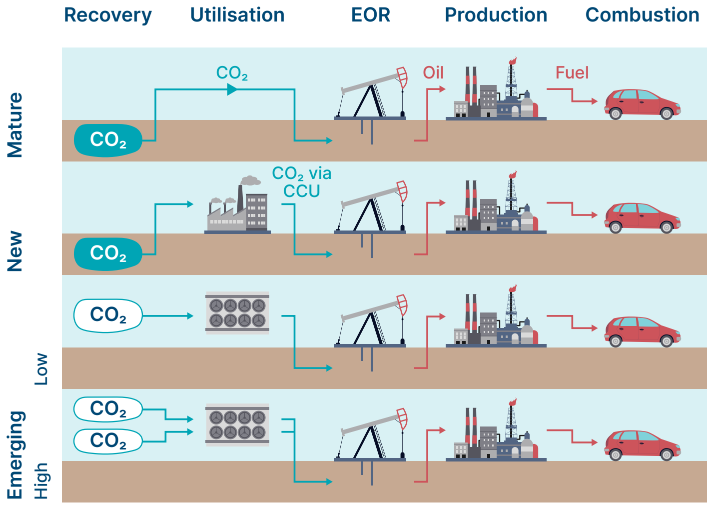
The ETC therefore believes that EOR should play only a minor role in the path to net-zero. In our scenarios we assume that 0.5 $GtCO_2$ will be injected into EOR operations in 2050. At a carbon intensity of 500 kg per bbl this will support the production of around 3.3 million barrels per day. The ETC believes that:

- Public policy should strongly favour forms of CO_2 CCUS other than EOR.
- Public policy should never support (and ideally discourage) mining CO_2 for EOR purposes.
- It should only support CO_2-EOR where the combination of CO_2 source and carbon intensity of injection delivers zero or negative net emissions.
- Claims of "carbon neutral" or "zero-carbon" oil should only be made if the net emissions effect is zero or negative.

Net CO_2 emissions from oil produced via EOR vary according to where the CO_2 is sourced from and the ratio of CO_2 injected to oil recovered

CO_2 emissions from EOR by recovery source and intensity

$kgCO_2/bbl$



Source	CO_2 source	Injection	Production	Combustion	Net emissions
CO_2 resevoir	300	-300	100	400	**500**
Point source capture	300	-300	100	400	**500+ utility**
DACCS & low case CO_2 ratio	0	-300	100	400	**200**
DACCS & high case CO_2 ratio	0	-600	100	400	**-100**

Exhibit 14

NOTE: Production includes processing, refining, transmission, distribution and retail.

SOURCE: Adapted from IEA (2019) *Can CO_2-EOR really provide carbon-negative oil?*

III. Plausible pathways to 2050 – accelerating progress in the 2020s

- 7 to 10 $GtCO_2$ per year capture capacity will be needed by 2050, compared with less than 40 Mt in operation in 2020.
- Growth of industrial and power plant application will be fastest in the 2030s while DACC growth will be concentrated in the late 2030s and 2040s, but significant development in the 2020s is needed to make the subsequent path feasible.
- Total capital investment required to deliver this pathway could reach almost $5 trillion over the next 30 years and exceed $400bn per annum by 2050 – a manageable figure within the context of the overall energy transition.
- Past growth has been slow with multiple project cancellations and disappointing cost-reduction. Partly this reflects improved economics for other decarbonisation levers but also policy and coordination failures which must be addressed.

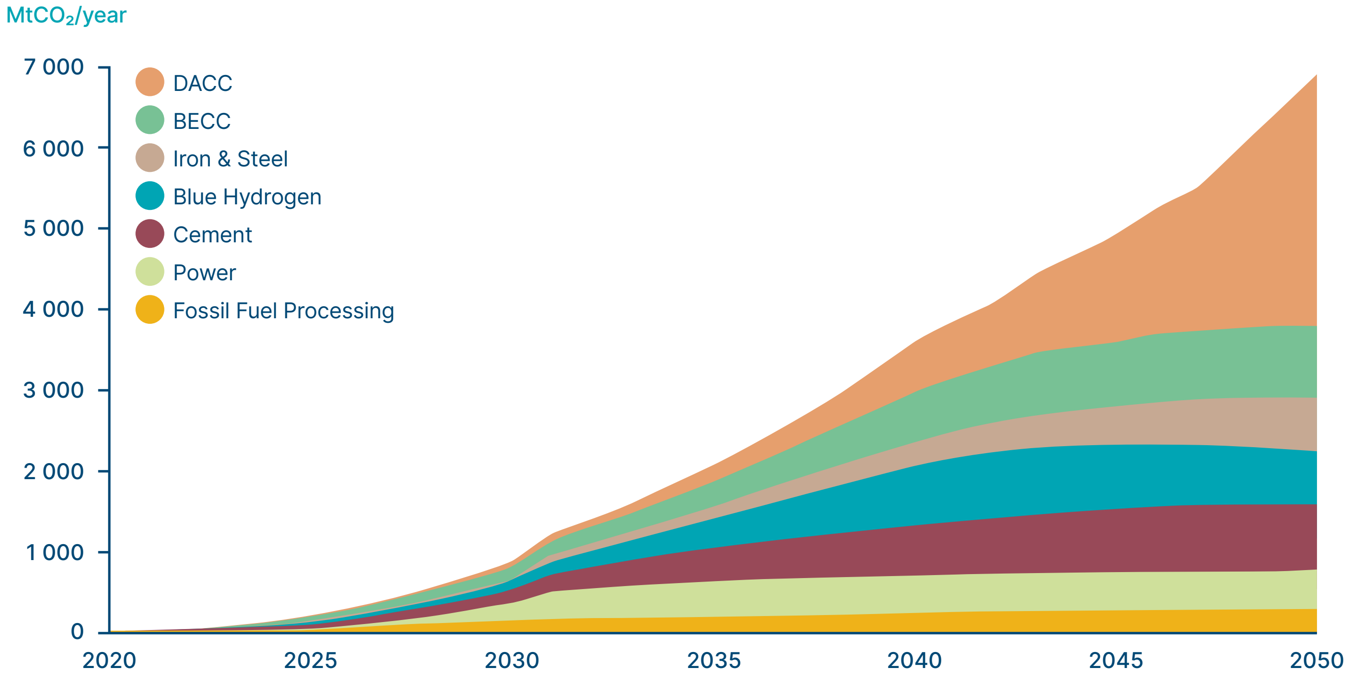
Pathways from now to 2050

The optimal rate of growth of CCUS deployment by sector will reflect both the technological readiness of carbon capture by sector and the economics of alternative decarbonisation pathways, which in turn are a function of uncertain future trends in technologies costs. As a result, specific sector pathways decade by decade are even more tentative than estimates of the scale of CCUS needed in 2050. But analysis of published sector decarbonisation plans, and

Exhibit 15

By 2050 direct air capture accounts for the largest share of CO_2 captured

CO_2 captured by sector in Base scenario



SOURCE: SYSTEMIQ analysis for the ETC (2022)

assessment of technological readiness and potential cost competitiveness supports the indicative growth path by sector shown in Exhibit 15. This implies a need to scale from 0.04 Gt per year today, to 0.8 Gt per year by 2030 and 3.6 Gt per year by 2040. Key features of this possible growth path are:

- Growth from today's minimal scale to around 0.8 Gt by 2030 will be driven by point source capture across multiple sectors, with a minimal role for DACC.
- Accelerating expansion to 3.6 Gt per annum by 2040, will require continued significant growth in cement, chemicals and power, together with growth of DACC to at least 0.6 Gt per annum by 2040.
- Growth in the 2040s is dominated by DACC as the role of CCUS in several industrial sectors and in power reaches maturity, and in some cases, declines.

The technology readiness level (TRL) of specific carbon capture technologies varies substantially, with some technologies still at prototype stage and, while others have been in commercial use for years. Unsurprisingly, the capture technologies with highest TRLs tend to be associated with sectors already operating commercial CCUS capacity, while technologies at a low TRL will be applied in future to sectors with limited CCUS uptake so far. This is illustrated in Exhibit 16.

- Early potential for the take-off of CCUS lies in power generation, natural gas processing, hydrogen, methanol, biomethane and some chemicals' production.
- CCUS is currently at demonstration stage in cement and high-value chemicals; this will make possible significant ramp-up in the 2030s.
- Applications at prototype stage include DACC and iron & steel. Further R&D is required in the 2020s and 2030s to support subsequent growth in these sectors.

High TRL CCS sectors drive capacity growth in the 2020s with less mature capture technologies ramping up in the 2030s and 40s

CO_2 captured by TRL in Base scenario

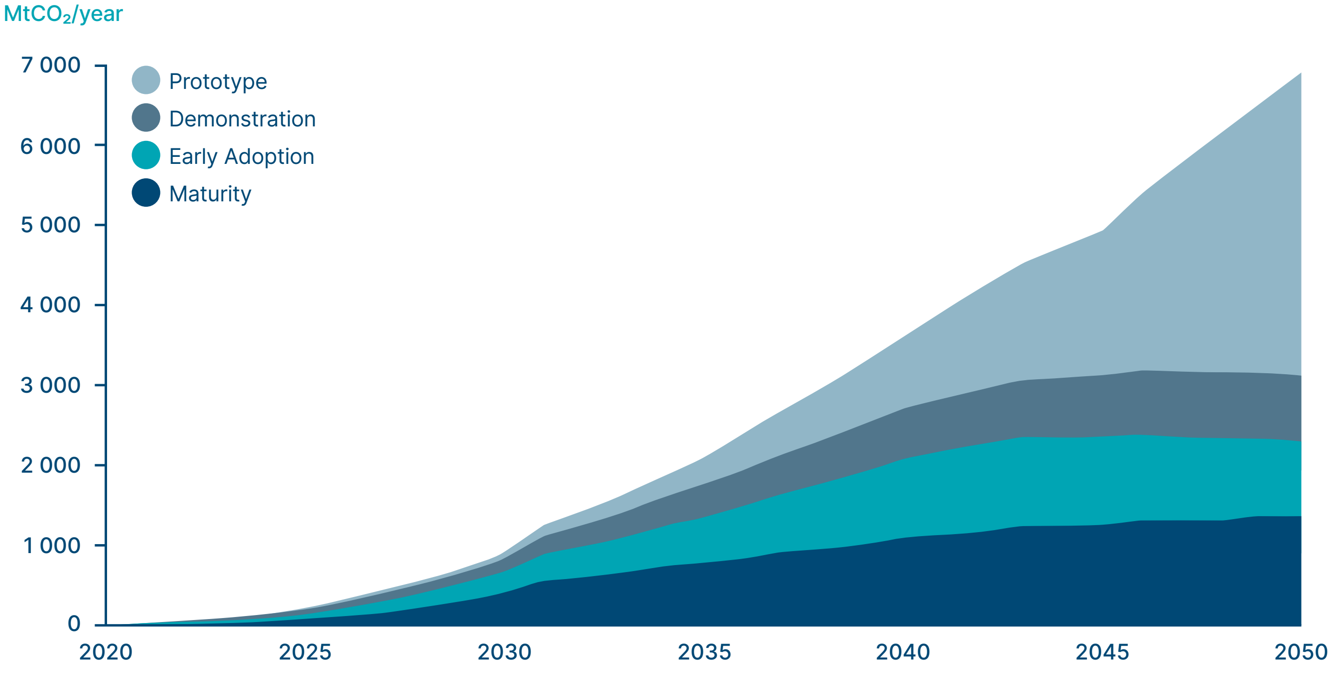


Exhibit 16

SOURCE: SYSTEMIQ analysis for the ETC (2022)

Total investment needs – large but manageable

To achieve the growth of CCUS shown in Exhibit 15 will require between $3.3–4.9 trillion of investments over the period from now to 2050, with annual investments potentially reaching $155bn in the early 2030s, rising to $300bn by the late 2040s (Exhibit 17). Of this total, the majority – between $2.6tn to $3.6tn across the period – will be directed towards capture capacity with between $0.8tn to $1.3tn needed for transport and storage infrastructure.

Investment in DACC accounts for the largest share of costs (especially once the significant clean power needs are also considered) but are inherently uncertain. DACC and associated power investments account for just under half of cumulative CAPEX requirements over the outlook (Exhibit 18).

- Future DACC CAPEX cost declines could drive investment needs anywhere from $0.6–1.3tn in the high case of 4.5 $GtCO_2$ capture, to $0.4–0.9tn in the base case of 3.5 $GtCO_2$ capture.[25] These conclusions are highly sensitive to assumptions concerning capital costs today, learning rates and efficiency gains.

- DACC CAPEX costs are realised primarily in the 2040s, when the technology is able to grow rapidly, with annual investments average between $60bn to $85bn per annum by 2045–50.

- Electricity investments required to build the wind and solar generation required to power DACC required an investment of between $0.9–1.2tn, in addition to the DACC.[26]

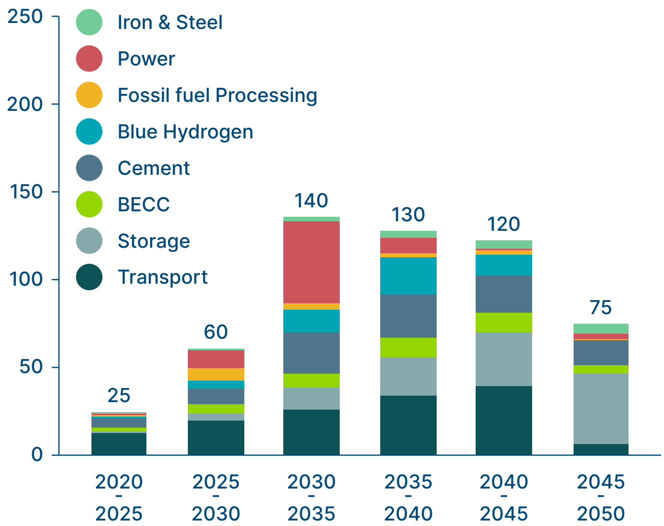
These capital investments are large but manageable within the context of an energy transition which is likely to require total capital investments of about $3.6 trillion per annum on average over the next three decades, the majority of which (around $2.9tn) is required to build a massively bigger global electricity production, transmission and distribution system. The ETCs forthcoming report on "Financing the energy transition" will assess investment needs and financing possibilities for all aspects of the transition to a zero-carbon economy.

25 This range reflects high (15%) and low (10%) learning rates applied to different capacities.
26 DACC power is modelled owing to the especially high energy costs associated with collecting CO_2 from low concentration levels. For point source capture methods, energy consumption relatively trivial and is treated as an operational expenditure, therefore not shown here.

Point source capture CAPEX peaks 2030 – 45 whereas DACC and associated power investment ramps up in the late 2040s

Average annual point source and T&S CAPEX 2020-50

$bn/year
(High deployment scenario, mid-cost assumptions)



Average annual DACC & DACC power CAPEX 2020-50

$bn/year
(High deployment scenario, mid-cost assumptions plus range)

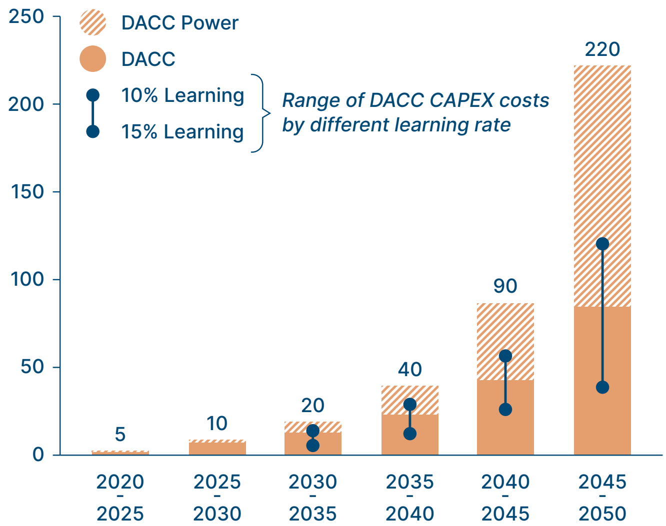


Exhibit 17

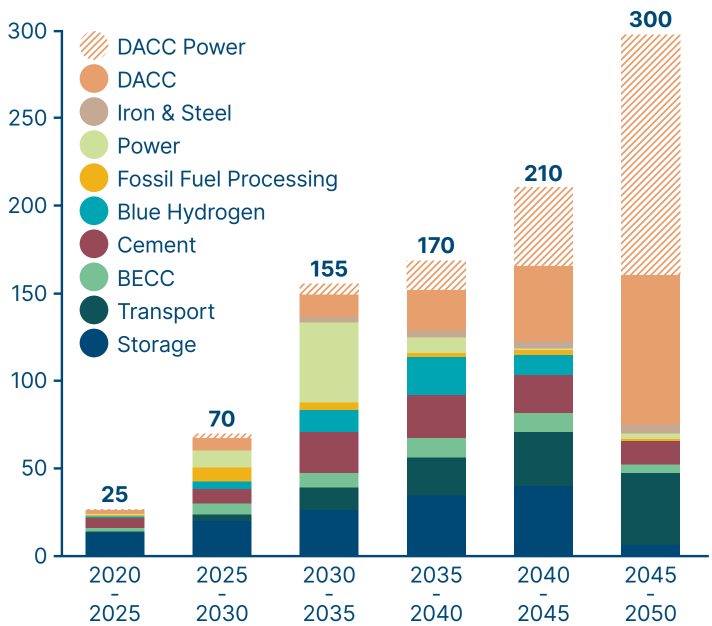
NOTES: Both charts show average annual CAPEX costs for “High Scenario” in which installed capacity reaches 4.5Gt by 2050. DACC power is shown owing to the especially high energy costs associated with collecting CO_2 from low concentration levels. For point source capture methods, energy consumption relatively trivial and is treated as an operational expenditure, therefore not shown here. DACC CAPEX bars show 12% learning rate, range indicates 15% learning (lower dot) and 10% learning rate (upper dot).

SOURCE: SYSTEMIQ analysis for the ETC

Average annual CAPEX reaches c. $300bn per annum in the late 2040s driven by DACC capacity deployment and associated power investment

Average annual CAPEX by sector 2020-50

$bn/year (High deployment scenario)



Cumulative CAPEX by sector and scenario 2020-50

$bn

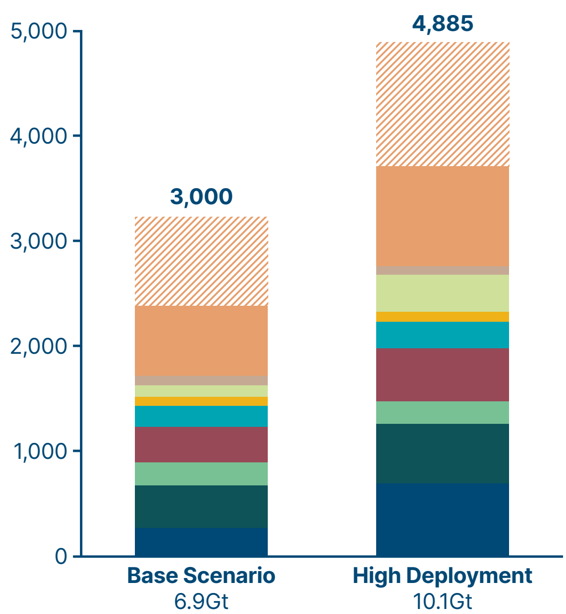


Exhibit 18

NOTES: DACC power is modelled owing to the especially high energy costs associated with collecting CO_2 from low concentration levels. For point source capture methods, energy consumption relatively trivial and is treated as an operational expenditure, therefore not shown here. High deployment scenario refers to 10.1GtCO_2 CCUS capacity by 2050 in which supply side decarbonisation measures only are deployed. Base Scenario sees 6.9GtCO_2 CCS capacity by 2050 as supply side decarbonization supported by energy productivity improvements as well.

SOURCE: SYSTEMIQ analysis for the ETC

Current plans by sector – falling far short of 2030 requirements

The pathways set out above imply an aggregate capture capacity of ~800 million tonnes per annum across all sectors by 2030. Existing plants already in production, together with 105 currently planned projects, would result (if all the new projects were successful) in 260 Mt per annum (Mtpa) of total capacity by 2030: 640 Mtpa short of our scenario. Meeting this shortfall would require around 200 additional CCUS-capable facilities to enter service by 2030.[27] Given the long lead times associated with developing CCUS projects, this will require projects to be initiated in the first half of the 2020s, and actions to be taken to accelerate project development timeframes wherever possible.

Slow progress over the last 15 years – reasons, lessons learned and how to move forward

Achieving the growth required in the 2020s would entail a dramatic change in trend, after a decade in which the number of operating plants has grown at a glacial pace and many announced projects have been abandoned.[28]

It is therefore important to understand why past growth has fallen far below expectations and what lessons can be learned for policy and focus going forward. There are four key reasons behind the slow progress of CCUS in the 2010's:

- **The relative economics of CCUS and that of low-carbon alternatives** has shifted dramatically in favour of the latter over the past decade, muddying the vision for CCUS deployment. Whereas CCUS was once viewed as having a prominent future role in power decarbonisation, the falling costs of wind and solar have severely diminished its likely role in that sector. Conversely, the necessary role of CCUS in sectors such as cement has only become apparent over the last decade as industry and policymakers have focussed on the need to achieve zero emissions even in the hard to abate sectors of the economy.

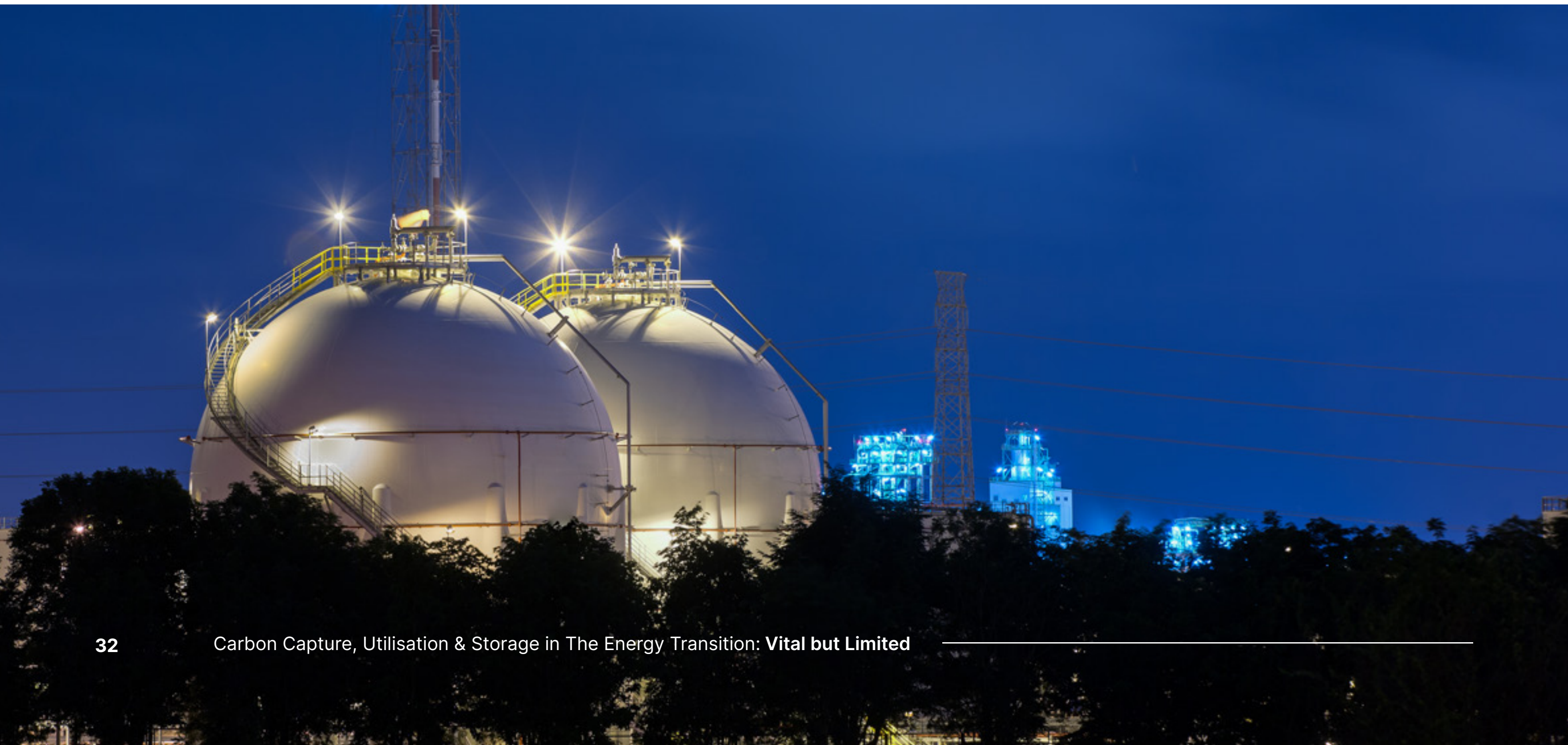
- **A lack of coordination of asset buildout** has left project developers needing to manage 'cross-chain' risks across three different types of assets: capture, transport and storage. Risks include counterparty default and volume uncertainty leading to underutilisation of assets. As a result there is a potential "first mover disadvantage" for investors who invest in the one element within the total required system.

- **Technical challenges** have beset many CCUS projects, including low capture rates and difficulty scaling up projects from pilots to larger scale. Additionally, though CCUS is deployment ready in many sectors, in others it remains low TRL.

- **A lack of public acceptance in some regions**, based on a perception that promises of future CCUS deployment are used to legitimise continued reliance on fossil fuels. This is compounded by a negative feedback loop where failed or underperforming projects have led to perceptions that the technology doesn't really work.

27 This figure is derived from the 2030 sectoral breakdown of CCUS capacity requirements, divided by the expected average CCUS plant capacity (by sector) minus the number of plants already in operation and in the pipeline.

28 Abdulla et al (2021) *Explaining successful and failed investments in U.S. carbon capture and storage using empirical and expert assessments*; Robinson R. (2016) *Offshore Megaprojects - Why we fail and how to fix it.*



Having failed to develop at scale over the past decade, the vital but limited role of CCUS as a complement to other low-carbon vectors in reaching net-zero is now much clearer, providing a way forward for CCUS deployment. Achieving the required acceleration will require 4 sets of actions:

1 *Getting the economics right*

In the case of some other decarbonisation technologies – in particular renewable electricity and green hydrogen – it is possible (and in some applications already certain) that the new technology will be lower cost than the old fossil fuel one. Conversely, CCUS will always be a more expensive option since it entails taking an existing process and adding CCUS. It will therefore always require some form of regulatory support.

- In the short-term this could entail the same sort of policies which have supported other technologies in the early stages of deployment – such as support for R&D, capital grants and state backed loans for specific first of a kind projects, or tax credits or contracts for difference supporting CCUS deployment on a technology specific basis.

- In the longer term, support should shift to technology agnostic mechanisms which advantage low-carbon materials and production processes over high-carbon ones, but leave it to the market to decide the relative role of CCUS versus other decarbonisation technologies. These policies should ideally include carbon pricing preference for low-carbon materials in public procurement, and mandatory requirements for low-carbon end products (Exhibit 19). Public procurement in particular offers a convenient means of generating significant demand for low-carbon products, with the impact of CCUS a small fraction of the overall product cost. For example, nearly 40% of concrete sold in North America is ultimately paid for by the state[29] – this represents a substantial opportunity to support scale up.

Technology specific support should gradually decline as technologies mature; carbon pricing, standards and mandates can remain indefinitely

Evolution of support for carbon capture

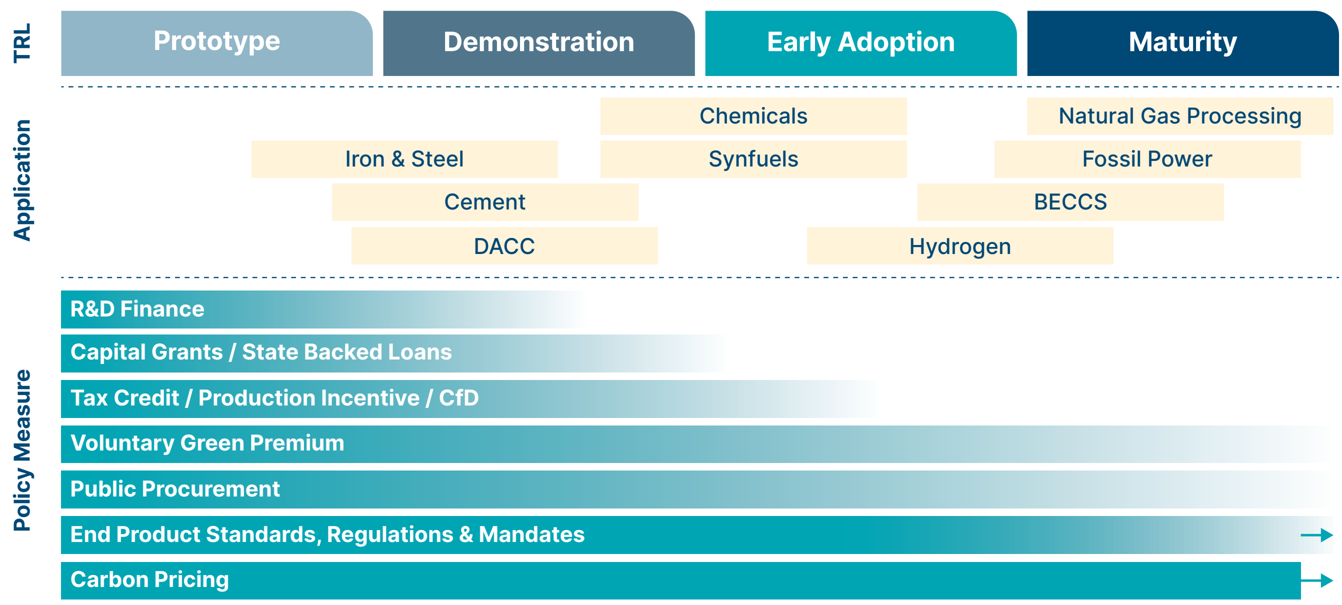


Exhibit 19

NOTES: These support measures pertain to carbon capture projects only. Regulated revenue streams are required in order to deliver – and share the costs of - the supporting T&S infrastructure (see Section 3.4.3).

SOURCE: adapted from IEA (2020) *Energy Technology Perspectives 2020: Special report on CCUS*

29 Total cement consumption in the U.S. was 98.5 million tonne (Mt) in 2018. From that, around 45 Mt was used in public constructions, paid for ultimately by the government. Source: Global Efficiency Intelligence (2021) *Federal Buy Clean for Cement and Steel: Policy Design and Impact on Industrial Emissions and Competitiveness.*

② *Addressing technical and cost challenges*

Deployment of CCUS technologies to date has been sporadic, with projects designed on a bespoke basis limiting the potential for economies of scale. Larger scale deployment of CCUS should lead to opportunities for resolving technical challenges through learning-by-doing, repeat design and industry knowledge-sharing.

Innovation in business models and design also offers prospects for resolving technical challenges. For example, modularisation of carbon capture processes could see standard, stackable, capture units deployed at sites of varying total size. Separately, business models such as 'Capture as a Service' could see dedicated players taking full responsibility for development of the capture at sites, avoiding the need for plant operators to integrate CCUS into their sites themselves.

③ *Resolving coordination issues*

Given the economies of scale for transport and storage (T&S) infrastructure (described in Chapter 2 of the main report) and the fact that sufficient T&S capacity is a precondition of capture asset development, CCUS projects are likely to benefit from the coordinated development of shared infrastructure in the form of industrial hubs or clusters. These bring together multiple CO_2 emitters/off-takers and at least one storage operator, through shared transportation infrastructure. Industrial CCS hubs can enable:

- **Reduced transport and storage costs**. 'Clustered' industrial sources can utilise shared T&S infrastructure thus reducing the cost of CCUS for individual customers[30] – particularly smaller entities which do not have the capacity to undertake major T&S infrastructure investments.[31] The colocation of multiple CO_2 capture and/or utilisation facilities using shared T&S infrastructure can reduce capture projects' breakeven thresholds by as much as 25%.[32]

- **Active cross-value chain collaboration between corporates**, including risk-sharing and co-funding agreements (as is occurring in many CCUS hubs today).

- **Tactical project location and delivery to shorten overall project delivery times**. For example, selective storage site development to reduce data gathering and appraisal, combined with accelerated capture technology and transport infrastructure delivery timelines can reduce overall project timelines from 7-10 years to as little as 5 years.[33]

- **Coordinated public policy support** which otherwise may not occur due to the dispersed nature of the benefits.

So-called 'anchor' projects, which account for a significant proportion of the total CO_2 captured at a hub may further accelerate CCUS development, by providing a large early-user of T&S infrastructure and bearing much of the fixed costs of the initial infrastructure.[34]

Public support can accelerate hub development in multiple ways. Governments can expedite the development of industrial CCS hubs by designating industrial zones and coordinating the planning process. Additionally, the development of pipelines and storage assets can be accelerated through appropriate funding models. T&S services are natural monopolies hence governments and regulators have a role to play in ensuring operators can make sufficient returns to incentivise investment whilst also protecting capture entities (i.e. regulated asset base models or price regulation).

Finally, contract negotiations both at the outset of the project and during construction if/when problems arise can be extremely time consuming. One solution to this is for governments and industry to develop a template commercial agreement in which risk and reward are clearly allocated between the various parties, including the government.

30 Ibid.
31 Global CCS Institute (2015) *The importance of CCS Hubs and Clusters.*
32 Wood Mackenzie (2021) *Carbon capture and storage: how low can costs go?*
33 SYSTEMIQ analysis for the ETC (2022).
34 Global CCS Institute (2016) *Understanding Industrial CCS Hubs and Clusters.*

④ *Addressing public opposition*

Public opposition has contributed to the cancellation of some projects such as the Barendrecht project in the Netherlands, and some countries, for instance Austria, have clear public policies to prohibit CCS development.

Overcoming public opposition to CCUS is likely to be contingent on:

- Government and industry setting out clearly the case for believing that CO_2 can be safely and permanently stored if projects are well managed.
- Regulators putting in place strong regimes and monitoring systems to ensure that storage projects use best management techniques and that project developers face clear liability for project failure.
- Policy-makers ensuring that clarity on the role of CCS projects: that carbon capture technology is utilised in addition to (not instead of) a rapid decline in emissions and associated fossil fuel use.
- Industry going beyond the minimum disclosure requirements where possible and being transparent on performance.

IV. Required action by industry and policy makers

There is no single global body which can set targets for CCUS, but to guide coordinated action from industry, corporates and governments it is useful to describe the scale of carbon capture, utilisation and storage which needs to be achieved by 2030. An indicative scale of ambition for 2030 is set out in Box 2.

Scale of CCUS deployment needed by 2030

Box 2

CAPTURE

- 0.8 $GtCO_2$ per year of capture across a suite of technologies by 2030, including carbon dioxide removal, cement, blue hydrogen, iron and steel, petrochemicals and fossil fuel processing, power generation and synthetic jet fuel.
- Active carbon capture at over 300 large industrial, energy production or carbon dioxide removal facilities, up from just 30 today.
- High capture rates at the majority of facilities, targeting 90%+ capture

TRANSPORT & STORAGE

- ~5 $GtCO_2$ storage capacity will be required for the period between 2030-2035 with action required to bring the sites from theoretical potential to injection ready, with 0.5 $GtCO_2$ per year being injected in 2030, and additional test injections at sites under development.
- Around 100 CCS hubs in operation around the world, benefitting from economies of scale and shared access to CO_2 transportation networks and storage.[35]

RESEARCH & DEVELOPMENT

- R&D and demonstration stage support targeting high efficiency operation, high capture rates and cost reductions across the CCUS value chain.
- Large active demonstration scale projects in cement, iron and steel and DACC ready for commercial scale deployment in the 2030s and 2040s.

INVESTMENT

- At least a 2x increase in investment into CCUS capacity and supporting infrastructure, from \$3bn today to ~\$70bn per annum by 2030.

Key actions for the 2020s

Collective action by government, corporates and investors will be critical to achieving this scale of CCUS in the next decade. The six broad categories of action which must be taken in the 2020s are described in Exhibit 20. Specific policies to drive this scale of development will need to reflect national and regional circumstances and should be informed by indicative targets for development at national/regional level.

To deliver these actions will require action by governments – acting either directly or as regulators – by oil and gas companies , other industries and finance providers. The role for each of these parties is described below and in Exhibit 20.

35 There will be some overlap between the CCS hubs and the 300 large industrial facilities.

Public and private sector entities have different roles to play in delivering CCUS scale up

6 strategies to drive CCUS expansion

Strategic category	Actions	Government	Regulators	Industry	O&G firms	Finance Players
1 Overcoming the Green premium to make early CCUS deployment economic	**Carbon Pricing:** a substantive economy-wide carbon price to provide a common, long-term decarbonisation signal for investors.	●	●			
	Direct state financial support: Technology specific grants and fiscal measures to overcome First-of-a-Kind costs.	●				
	Other actions to overcome 'the green premium': De-risking mechanisms such as Contracts-for-Difference; building early markets for low-carbon products produced using CCUS (such as building materials) through public procurement, voluntary green premiums (whereby companies choose to purchase low-carbon goods) and/or product standards, regulations or mandates; tax incentives.	●		●	●	●
2 Building the enabling infrastructure	**Shared cost models and scale up of T&S infrastructure:** effective coordination and zoning actions by government alongside business model innovations from industry to accelerate the development of CCUS hubs; significant, early investment from industry and financial players, ensuring sufficient spare T&S capacity to enable FID on new capture projects.	●	●	●		●
	Storage surveys & test injections: accelerate development of 'injection-ready' storage sites ahead of need via public funding for surveys and test wells, leading to freely available "atlas" of saline aquifers.	●		●	●	
	Reusing oil and gas infrastructure: Repurposing decommissioned oil and gas reservoirs as a low cost, near term source of new storage capacity.			●	●	
3 R&D and deployment support for new technologies	**Support capture innovation:** public funding through grants, competitions and regulatory models focussed on proving low TRL capture technologies at industrial scale (cement, iron & steel, DACC) and improving capture rates/efficiency for higher TRL sectors (power, chemicals, hydrogen).	●		●	●	●
	Business Model Innovation: development of new commercial models such as Carbon capture as a Service which can lower technology and financing costs – e.g. through replicable designs, modularisation, or smaller industrial footprints.			●	●	●
4 Clear risk allocation to ensure responsible and secure CCUS development	**Regulation and assignment of liability:** clear delineation over who has responsibility for CO_2 at each stage in the CCUS value chain; well defined standards regardng capture rates and quality of products utilising CO_2.	●	●	●		
	State backed insurance for storage: public involvement via financial backing for insurance against leakage or possibly assuming liability for long term CO_2 storage.	●	●			●
	Counterparty risk mitigation: guarantees and infrastructure coordination in order to mitigate risk of stranded assets and first-mover disadvantage.	●	●			●
5 Developing standards and monitoring to ensure lowest carbon CCUS	**Monitoring for CO_2 leakage:** real time monitoring of pipelines and storage sites via novel technologies such as satelite immagery, facilitating enforcement of the rules and building best practice.		●	●	●	
	Validating emissions intensity of energy inputs: ensuring energy used as an input into CCUS processes is truly zero/low carbon in order to provide accurate assessment of end impact on CO_2 levels.		●	●	●	
6 Building public support for an appropriate and focused use of CCUS	**Clear policy on the role of CCUS:** clear messaging on the limited but vital role CCUS can play, acknowledging the limits of this technology as a policy option.	●		●	●	●
	Transparency on performance: build trust in the technology, the industry and related institutions through regular, accurate, detailed publication of performance reviews in regards to capture rate and leaks.	●	●	●	●	●

Exhibit 20

SOURCE: SYSTEMIQ analysis for the ETC (2022)

Governments

Governments have an essential part to play in setting policy which clearly defines CCUS' role (and its limits) in the energy transition and providing regulatory and financial support where necessary – notably with regards to carbon pricing but also in the form of public funding for R&D into low TRL capture, geological appraisal of potential storage sites and state backed insurance. Government also has a role to play in facilitating development through centralised coordination and helping to overcome risks (e.g. contract templates, industrial cluster planning or counter-party guarantees).

Regulators

Regulators are key to defining the details and ensuring compliance. Well defined standards, responsibility for CO_2 at each stage of the value chain and penalties for non-adherence (i.e. carbon leakage) are critical not only for building business confidence and encouraging investment but also in overcoming public opposition. In the same vein, regulators must be allowed to monitor industry's performance (notably capture rates and leakage from T&S) and where necessary impose meaningful fines for non-compliance.

Industry

Industry (capture facilities, T&S operators and supply chain) is the engine of innovation. Significant cost declines and capacity scale up are required in order to meet the carbon capture volumes set out in this report. Industrial innovation has a key role not only in delivering technological improvements (improving capture rates and reducing costs) but also in regards to business models: innovative approaches such as Capture as a Service will be critical to extending CCUS from very large players to mid-cap entities. Industry (alongside government) also has a key role to play in the coordination and development of CCUS industrial hubs.

Oil and gas firms

Oil and gas firms in particular have a key role to play in driving CCUS expansion. The sector's knowledge and expertise regarding geology, gas transportation and subterranean sequestration are likely to be valuable in this endeavour. The industry is likely to be involved in carbon capture in blue hydrogen development, and from fossil fuel processing and refining.

Finance

The scale of the investment required in delivering CCUS growth means that financial firms must play a key part: although government has a role to play in supporting FOAK projects, R&D and underwriting some niche liabilities, the vast majority of finance for the CCUS industry will come from the private sector. In particular, financial entities can leverage expertise in ensuring credit flows to the necessary sectors whilst utilising innovative financial tools to help mitigate risks.

Acknowledgements

The team that developed this report comprised:
Lord Adair Turner (Chair), Faustine Delasalle (Vice-Chair), Ita Kettleborough (Director), Mike Hemsley (Head of Analysis), Kash Burchett (Lead author), Andrea Bath, Tassilo Bismarck, Leonardo Buizza, Maximilian Held, Michael Kast, Philip Lake, Elizabeth Lam, Hugo Liabeuf, Chelsea Maffia, Tommaso Mazzanti, Hettie Morrison, Shane O'Connor, Sanna O'Connor-Morberg, Caroline Randle, Carolien van Marwijk Kooy, Rafal Malinowski, Andreas Wagner (SYSTEMIQ).

The team would also like to thank the ETC members and experts for their active participation:
Clive Turton (ACWA Power); Elke Pfeiffer (Allianz); Nicola Davidson (ArcelorMittal); Tara Shirvani (Autonomy Capital); Abyd Karmali (Bank of America); Paul Bodnar, Michelle Bolten (Blackrock); Julia Atwood, David Madrid Garcia and Albert Cheung (Bloomberg NEF); Doris Fujii, Martin Towns, Will Zimmern (BP); Jeanne Ng (CLP); Vivienne Yang (Credit Suisse); Anupam Badola, Ashwani Pahuja (Dalmia Cement (Bharat) Limited); Yi Zhou, Bin Lyu (Development Research Center of the State Council); Tanisha Beebee and Cat Reynolds (DRAX); Adil Hanif (EBRD); George Wang, Olivia Sang (Envision); Phillip Niessen (European Climate Foundation); Eleonore Soubeyran (Grantham Institute, London School of Economics); Matt Gorman (Heathrow Airport); Øystein Kostøl (Hegra); Andrea Griffin, Abishek Jospeh (HSBC); Francisco Laveran (Iberdrola); Chris Dodwell (Impax Asset Management); Yanan Fu (Institute of Climate Change and Sustainable Development, Tsinghua University); Ben Murphy and Andrew Symes (IP Group); Simon Gadd (L&G); Vincenzo Cao (LONGi Solar); Christopher Kaminker (Lombard Odier); Jazib Hasan (Modern Energy); Matt Hinde (National Grid); Emil Damgaard Gann (Ørsted); Vivien Cai, Summer Xia (Primavera Capital); Manya Ranjan (ReNew Power); Jonathan Grant (Rio Tinto); Greg Hopkins, Cate Hight, Caroline Zhu, Xangzi Lu, Shuyi Li, Rudy Kahsar and Guy Wohl (Rocky Mountain Institute); Charlotte Brookes (Royal Dutch Shell); Emmanuel Normant (Saint Gobain); Vincent Petit (Schneider Electric); Brian Dean (SE4All); Camilla Palladino (SNAM); Martin Pei (SSAB); Alistair McGirr (SSE); Abhishek Goyal (Tata Group); Madhulika Sharma (Tata Steel); A K Saxena (TERI); Reid Detchon (United Nations Foundation); Mikael Nordlander (Vattenfall); Niklas Gustafsson (Volvo Group); Rasmus Valanko (We Mean Business); Rowan Douglas (Willis Towers Watson); Jennifer Layke (World Resources Institute); Mark Trueman (Worley).

The team would also like to thank the ETC's broader network of experts for their input:
Will Lochhead (BEIS); Jonas M. Helseth (Bellona); Brent Constantz (Blue Planet); Eric Trusiewicz (Stanford University); Ffion Rolph and Selina Good (Carbon8); Aniruddha Sharma (Carbon Clean); Hannah McLaughlin, Helen Bray (Carbon Engineering); Mike Childs (Friends of the Earth); Guloren Turan (Global CCS Institute); Doug Parr (Greenpeace); Noah McQueen (Heirloom); Phil Renforth (Herriot Watt University); Samantha McCulloch (IEA); Sylvain Thibeau, Nirvasen Moonsamy and Julien Perez (OGCI); Sachin Kumar and Shruti Dayal (TERI); Stuart Haszeldine (University of Edinburgh); Gareth Johnson (University of Strathclyde); Dr. Gabrielle Walker (Valence Solutions); Brian Baynes (Verdox); Nicky Ison (WWF).

The ETC would like to acknowledge in particular the contribution of John Scowcroft of the Global CCS Institute, who sadly passed away before this report was published. John provided many valuable insights over the course of the research and we are extremely grateful to him for his contribution.

The **Making Mission Possible** Series

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July 2022

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