

The Carbon Sequestration Leadership Forum

The Carbon Sequestration Leadership Forum (CSLF) is a ministerial-level international climate change initiative that is focused on the development of improved cost-effective technologies for carbon capture and storage (CCS). The Forum also promotes awareness and champions legal, regulatory, financial, and institutional environments conducive to such technologies.

The 26 CSLF member governments (25 countries plus the European Commission) represent over 3.5 billion people (60% of the world's population) on six continents and comprise 80% of the world's total anthropogenic carbon dioxide (CO₂) emissions.

The current members of the CSLF are Australia, Brazil, Canada, China, the Czech Republic, the European Commission, France, Germany, Greece, India, Italy, Japan, Korea, Mexico, the Netherlands, New Zealand, Norway, Poland, Romania, Russia, Saudi Arabia, Serbia, South Africa, the United Arab Emirates, the United Kingdom, and the United States.

Foreword

CSLF issues technology roadmaps (TRMs) for carbon capture, utilisation and storage (CCUS) at regular intervals. This 2021 edition is an update of the 2017 version.

Several countries have issued national strategies that, to some extent, are referenced here. An updated TRM from CSLF will, however, contribute to a common understanding among CSLF, Clean Energy Ministerial (CEM) CCUS, and Mission Innovation (MI) members regarding:

- The role of CCUS in decarbonizing society.
- The status of CCUS.
- Important and necessary developments to speed up implementation of CCUS.

Furthermore, a common TRM will:

- Reach the wide membership of CSLF and CEM CCUS.
- Help countries developing national strategies on CCUS.
- Be an important tool in communicating the need and role of CCUS.

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Executive Summary

This Carbon Sequestration Leadership Forum (CSLF) 2021 Technology Roadmap (TRM) is an update of the 2017 version, based on reported progress and published documentation on carbon capture, utilisation and storage (CCUS) activities between October 2017 and February 2021.

The main findings of the 2021 Technology Roadmap are as follows:

- 1. By the end of 2020, the world was not on track to reach the targets of the Paris Agreement of keeping the anthropogenic temperature rise to well below 2°C, and preferably close to 1.5°C, by the end of the 21st century.**
 - Global energy-related carbon dioxide (CO₂) emissions have steadily increased over the past ten years, reaching 33.4 billion metric tons (Gt) in 2019. Despite a significant overall decrease in emissions in 2020 due to the COVID-19 pandemic, emissions were again on the increase in December 2020, and it is likely that they will increase significantly in 2021.
 - As regards mitigation actions by governments, recent analysis by the United Nations Framework Convention on Climate Change (UNFCCC) indicates that the set of measures included in current nationally determined contributions (NDCs) would result in only a 0.5% drop in emissions by 2030, compared with the 25% decrease that is necessary. Actions are thus far from being enough to decrease emissions at the rate needed.
 - Strong efforts in post-COVID-19 recovery plans are needed to sufficiently decarbonize the economy.
 - There is reason for optimism, as many countries have reported ambitious new climate targets and low-carbon measures in their submissions to the Paris Agreement and COVID-19 recovery plans.
- 2. Carbon capture, utilisation and storage, or CCUS, will be required to meet the targets of the Paris Agreement.**
 - A great majority of climate scenarios show that CCUS will play a crucial role in reducing direct emissions from industrial processes and the use of fossil fuels in power generation, industry, and fuel transformation. CCUS is particularly important for hard-to-abate industries.
 - Modelling suggests that, without CCUS, it becomes nearly impossible and more costly to reduce CO₂ emissions sufficiently fast to keep global warming well below 2°C.
 - CCUS will be needed with bioenergy, direct air capture, or other technologies to remove CO₂ from the atmosphere at a scale that leads to net negative emissions.
 - CCUS can also provide other societal benefits.
 - Technologies for the elements along a CCUS chain—capture, transport, and storage—have been demonstrated in large-scale projects, and deployment can start with existing technologies.
- 3. There has been progress in many aspects of CCUS since the 2017 TRM.**

Project developments

- One industrial CO₂ infrastructure project, the Alberta Carbon Trunk Line (ACTL) in Canada, came into operation.
- One large-scale project in Australia, the Gorgon project, came into operation in 2019 and is expected to become the world's largest carbon capture and storage (CCS) project.
- One industrial CO₂ infrastructure project, The Longship in Norway, passed final investment decision (FID).
- Several other industrial CO₂ hubs have been identified and are moving to planning stages.

Technology developments

- Capture costs have been reduced through research, development and demonstration (RD&D), as exemplified by the baseline cost that is 15%–20% down the last decade.
- Progress has been made in modelling and monitoring for geologic storage of CO₂, for example, in Otway Stage 2C in Australia.
- CO₂ storage sites have been characterised, including CarbonNet in Australia, CarbonSAFE in the United States of America, and the Northern Lights in Norway.
- Negative emission technologies (NETs) have been demonstrated (bioenergy with CCUS) or brought to pilot and demonstration phases (mineralisation and direct air capture).
- Various CO₂ utilisation technologies have been commercialized, and many others are being further explored.
- Transfer of experience and knowledge from large-scale projects is taking place continuously.
- Hydrogen production from natural gas with CCUS has emerged as a measure that will contribute to a rapid transition to a hydrogen society, with cost and carbon footprint competitive with hydrogen from electrolysis in the short to medium time frame.

Policy and legal developments

- Several ambitious climate strategies aiming at reaching net-zero emissions by mid-century have been put forward by countries and regions, providing a critical backdrop for various measures to curb greenhouse gas (GHG) emissions.
- In parallel, several countries have put in place new national strategies and incentive frameworks for CCUS, including large-scale projects, provision of capital support, support for increased operational expenditures, and political backing for industrial CCUS hubs. These will be important drivers for CCUS deployment.
- The earlier barrier in the London Protocol to allow export of CO₂ for offshore geological storage has been removed by allowing provisional application of the Amendment.
- International standards and recommended practises have been developed, as have rules and recommendations for sustainable finance, both of which can act as catalysts for CCUS investment.

4. The deployment of CCUS lags behind what is required even in the scenarios of the International Panel on Climate Change (IPCC) and International Energy Agency (IEA) with highest ambitions on the implementation of other sustainable measures.

- At the end of 2020, the global carbon capture and injection capacity in operation was approximately 40 million metric tons (Mt) CO₂/year.
- Projects under planning and that may come online in the period 2025–2030 may add less than 300 Mt CO₂/year, 50% of what is needed in the IEA Sustainable Development Scenario (SDS).

5. The CSLF Technical Group stresses the challenging deployment pathway for CCUS in the coming decades, based on the IEA SDS:

- By 2030: The isolation from the atmosphere by CO₂ capture and storage should have increased by a factor of 10–15 from the 2020 level of 40 Mt CO₂ per year.
- By 2050: The isolation from the atmosphere by CO₂ capture and storage should have increased by a factor of 100 or more from the 2020 level of 40 Mt CO₂ per year.

The CSLF Technical Group invites all its members, Clean Energy Ministerial members, and all other relevant countries, as well as industry and the financial sector, to join forces to work together to achieve rapid and tangible progress on the above pathway.

Recommendations:

Technology development, innovation, and cost reduction

- Investing heavily in RD&D to:
 - Reduce capture costs by 25% from the 2020 benchmark (\$60/t CO₂ avoided).
 - Bring enabling and emerging capture technologies to technology readiness level 7 or above.
 - Reduce storage monitoring and verification costs by 25% relative to 2020.
 - Mature sustainable NETs.
 - Continue the development and deployment of CO₂ utilisation technologies.
 - Develop novel, emerging, and enabling technologies along the whole CCUS chain.
- Transferring knowledge continuously from existing large-scale projects to new projects.
- Making investments in public–private partnerships or projects that continue to develop and mature promising utilisation technologies (technology push), including transparent methods for lifecycle analyses (LCAs) and techno-economic analyses (TEAs), and establishing a goal that a certain percentage of all government-procured products meet a low-carbon or “green” standard.
- Taking several actions in the science and technology of NETs and continuing to invest in transformational R&D and advance the most promising technologies to pilot scale and demonstration testing.

Strategic build-out of CCUS projects and hubs

- Making all efforts to ensure that all future projects under development today, or an equivalent volume of carbon capture capacity, are brought to operation.
- Rapidly identifying, planning, and building out strategic power and industrial CO₂ capture clusters, with common CO₂ transportation and storage infrastructure (hubs), to ensure a 10-fold increase of industrial production facilities and power and heat plants, including waste-to-energy plants, with CCUS by 2030. This will be essential for cost-effective CCUS.
- Implementing CCUS at a substantial fraction of fossil fuel hydrogen production facilities (for example, a fraction of one-third will be required in 2030 in the IEA SDS).
- Ensuring that sufficient CO₂ storage sites be characterized and developed, and necessary permits obtained.

Development of strategy, policy, legal, and financial frameworks

- Implementing policies to mitigate the impacts of climate change, and ideally, defining the role that CCUS can hold in a portfolio of responses.
- Developing national or regional CCUS strategies and implementation plans.
- Developing incentive frameworks, business models, and risk-sharing mechanisms that will enable CCUS projects to be financeable, including placing a value on CO₂ emissions reductions and differentiating between business and financial risks.
- Implementing legal, regulatory, and accounting frameworks to ensure safety and environmental integrity of CO₂ capture, storage, utilisation, and transport operations while ensuring regulatory pathways to support the operational aspects of projects.
- Implementing frameworks to enable cross-border transport of CO₂ for storage purposes.
- Communicating the importance of CCUS.
- Sharing best practices to foster cost reduction and to help countries and industries accelerate CCUS investment.

*Governments have a critical role in accelerating
the deployment of CCS.*

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1. Introduction

1.1. Objective and audience

The objective of the Carbon Sequestration Leadership Forum (CSLF) 2021 Technology Roadmap (TRM) is to provide an update of the 2017 edition (CSLF 2017a) on technology development status of carbon capture, utilisation and storage (CCUS), as well as provide recommendations on actions required if development and deployment of CCUS technologies are to give the necessary contributions in meeting the targets of the Paris Agreement.

The recommendations in this roadmap are directed to CSLF ministers, the Clean Energy Ministerial (CEM), and other climate and energy policymakers in governments and private enterprises. The CSLF Technical Group has proposed this roadmap for the CEM CCUS Initiative and CSLF Policy Group as formal input into the 2021 communiqué to the annual CEM meeting 2021.

With the release of this technology roadmap, the CSLF and CEM CCUS aspire to play important roles in reaching the targets set in the Paris Agreement by accelerating commercial deployment, and to set out key priorities for research, development, and demonstration (RD&D) of improved and cost-effective technologies for the separation and capture of carbon dioxide (CO₂), its transport, and its long-term safe storage or utilisation.

1.2. Background for update

There are several reasons behind a refreshment of the 2017 CSLF TRM:

- Several documents that emphasise the importance of CCUS have been issued, including the International Energy Agency (IEA) *Energy Technology Perspectives 2020* (IEA 2020a and IEA 2020b), the IEA *World Energy Outlook 2020* (IEA 2020c), the Intergovernmental Panel on Climate Change (IPCC) Special Report on *Global Warming of 1.5°C* (IPCC 2018), the Global Carbon Capture and Storage Institute (GCCSI) annual status reports that show the progress from year to year, International Organization for Standardization (ISO) standards¹, and new national and international regulations.
- A large number of reports and peer-reviewed articles on specific subjects treated in the 2017 TRM (CCUS in industry, CO₂ infrastructures, hydrogen production with CCS, etc.) have been published with new information.
- The interest in CCUS has shifted from pure technology development to integration, scale-up, and utilisation issues.
- Clean hydrogen has emerged as an important factor to reduce CO₂ emissions, and production from fossil fuels with CCS can supply competitive prices to other production methods.
- Last, but not least, there are clear signals from governments that they are ready to invest in CCUS, as seen in the United Kingdom², Norway³, the Netherlands⁴, and other countries.

¹ For an overview of CCUS-related ISO documents, see https://www.iso.org/search.html?q=carbon%20dioxide%20capture&hPP=10&idx=all_en&p=1

² https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/909706/CCUS-government-response-business-models.pdf; <https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution>

³ <https://www.regjeringen.no/en/aktuelt/the-government-launches-longship-for-carbon-capture-and-storage-in-norway/id2765288/>

⁴ www.rijksoverheid.nl/documenten/publicaties/2018/03/05/routekaart-ccs

1.3. Major differences between 2017 and 2021 Technology Roadmaps

In the 2021 Technology Roadmap, the time horizons for medium- and long-term targets have changed from 2025 and 2035 to 2030 and 2050, following the international trend for climate ambitions.

Section 2 has been updated with new scenarios from the IEA. These have led to targets that are based on the IEA Sustainable Development Scenario (SDS) (described in IEA 2019a and 2020a,b,c), rather than the IEA 2°C scenario (2DS) (IEA 2017). Differences are described in Section 2.2.2.

Other changes are found in the definitions of CCS, CCU, and CCUS for consistency with IEA.

Section 3 has been updated in sections on power, industry, and RD&D and expanded in sections on hydrogen with CCUS, CO₂ hubs, industrial CCUS, and CO₂ utilisation. A new section on negative emission technologies (NETs) has been added.

1.4. Scope of the CSLF 2021 Technology Roadmap

In 2019, the total greenhouse gas (GHG) emissions were 59.1 gigatonnes (Gt, or 10⁹ metric tons) CO₂e (United Nations Environment Programme [UNEP] 2020a), of which 35.8 Gt were from energy and process-related CO₂ emissions (IEA 2020c).

This updated CSLF TRM highlights advances in capturing, utilising, and storing CO₂ since the 2017 roadmap was issued. The 2021 TRM provides the CSLF member states with a strategic way forward on how CCUS applied to energy and process-related CO₂ emissions can contribute to reaching the goals of the Paris Agreement. It is hoped that this will facilitate an orderly and timely transition to a lower-emissions future. Other GHG emissions are outside the scope of this report.

1.5. Terminology

There appears to be no generally accepted terminology when discussing CCUS. This TRM has adopted the definitions of the IEA (2020b):

- CCS: Carbon capture and storage includes applications in which the CO₂ is captured and permanently stored.
- CCU: Carbon capture and utilisation, or CO₂ use, includes applications in which the captured CO₂ is used, for example in the production of fuels and chemicals.
- CCUS: Carbon capture, utilisation and storage includes CCS, CCU, and also where CO₂ is both used and stored, for example, in enhanced oil recovery (EOR) or in building materials, where the use results in *some or all* of the CO₂ being permanently stored.

These definitions differ from those in the 2017 CSLF TRM, the main difference being that CCUS in the 2017 TRM required that *all* CO₂ that was used would eventually be stored permanently after use, whereas the above definition of CCUS allows for storage of *some* of the CO₂.

Carbon dioxide removal (CDR) has received increased attention since the 2017 TRM. This is reflected in the 2021 TRM, where the following terminology is used:

- Negative emissions occur when a sink—created or enhanced by human activity—removes GHG from the atmosphere⁵ (in this TRM, only CO₂ is considered).
- Negative emissions technologies (NETs), sometimes also called carbon dioxide removal (CDR): Activities that remove CO₂ from the atmosphere and durably store it in geological, terrestrial, or ocean reservoirs, or in products. CDR includes enhancement of biological or geochemical sinks and direct air capture (DAC) and storage but excludes natural CO₂ uptake not directly caused by human intervention⁵.

⁵ <https://cdrprimer.org/>.

1.6. Impact of COVID-19 on energy use, CO₂ emissions, and the deployment of CCUS

The COVID-19 pandemic has had an exceptional impact on the economics of countries around the world, with severe effects on lives and livelihoods. COVID-19 has impacted energy use and CO₂ emissions and introduced near-term uncertainty about the future of energy demand. As of early March 2021, IEA⁶ estimates that the primary energy demand in 2020 dropped 4% from 2019 and that energy-related CO₂ emissions were down 5.8%, somewhat less than earlier estimates (IEA 2020c; DNV·GL 2020a; UNEP 2020a), all of which indicated that the energy demand would drop by 5% and the energy-related CO₂ emissions by 7% in 2020. An increase in emissions in December 2020 by 2% above December 2019 contributed to the difference in estimates. Energy investments are expected to be down 18% (IEA 2020c). There will be variations across fuels and nations.

Despite the reduction in CO₂ emissions in 2020, the world is still on its way to a temperature increase in excess of 3°C. The COVID-19 drop in emissions will have minimal impact—only 0.01°C—on the temperature increase by 2050 (UNEP 2020a).

DNV·GL (2020a) believes the CO₂ emissions peaked in 2019, brought forward some years because of the pandemic. The IEA (2020 a,b,c) expects the CO₂ emissions to reach 2019 levels and return to an upward trajectory after the pandemic, in a scenario in which development continues with the existing policy frameworks and today's announced policy intentions. In a sustainable development scenario, CO₂ emissions peaked in 2019 and will thereafter decline (see Box 2.1 for the IEA scenarios).

The global economic recession caused by COVID-19 is likely to affect energy investments, including CCUS. However, the inclusion of CCUS in recovery plans could help reduce the setback, this time with better success than in the recovery plans after the financial crisis in 2008–2009 (IEA 2020b). Without economic recovery plans' incorporation of structural changes towards decarbonation, the drop in CO₂ emissions in 2020 caused by COVID-19 will be only temporary and will not contribute significantly to emissions reductions by 2030 (UNEP 2020a; NewClimate Institute 2020).

⁶ <https://www.iea.org/articles/global-energy-review-co2-emissions-in-2020>

2. The Importance of Deploying CCUS

2.1. The need to reduce CO₂ emissions

In 2019, total energy-related direct global emissions of CO₂ amounted to approximately 35.8 Gt, distributed among sectors as shown in Figure 2.1. Estimates for 2020 indicate that CO₂ emissions were 33.4 Gt CO₂ because of the COVID-19 pandemic's impact on the world economy (IEA 2020c).

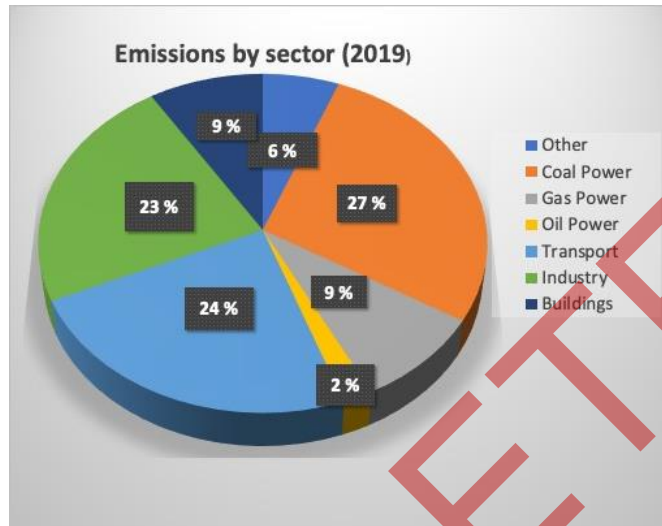


Figure 2.1. Global CO₂ emissions in 2019 by sector (based on data in IEA 2020a)

The IEA (2019; 2020 a,b,c), DNV·GL (2020a), UNEP (2020a), and Bloomberg (2020) have modelled future CO₂ emissions, using scenarios or forecasts based on today's policy intentions and targets. The modelling results vary with respect to reductions in CO₂ emissions; however, they all agree that the temperature increase by 2100 will exceed 2.5°C unless strong measures are taken^{7,8}; UNEP (2020a) says at least 3°C.

Various national strategies and policy initiatives for net-zero emissions goals have emerged, and it is expected that these policies will help drive CCUS deployment in the short to medium term (see Section 4).

All reports referenced above show that there is a great need to reduce CO₂ emissions if the world is to reach the targets of the Paris Agreement.

There is some reason for optimism, as many countries have reported low-carbon measures in their COVID-19 recovery plans (NewClimate Institute 2020).

2.2. The importance of CCUS, the industrial sector, and negative emissions

2.2.1. The role of CCUS in climate scenarios

A range of measures will be necessary to obtain the needed reductions, including avoided demand, improved technology performance, renewables, alternative fuels such as hydrogen, electrification, and CCUS. Peters and Soggnæs (2019) found that the majority of scenarios used by the IPCC (the *Fifth Assessment Report* [AR5], 2014, and the *Special Report on Global Warming of 1.5°C*, 2018)

⁷ See also <https://www.iea.org/data-and-statistics/charts/co2-emissions-reductions-by-measure-in-the-sustainable-development-scenario-relative-to-the-stated-policies-scenario-2010-2050>

⁸ <https://www.carbonbrief.org/profound-shifts-underway-in-energy-system-says-iea-world-energy-outlook>

and the IEA (SDS, described in IEA 2019a and 2020a,b,c) show a strong reliance on CCS to reduce direct emissions from the use of fossil fuels in power generation and industry. The technology will also play a role with bioenergy, direct air capture, and other technologies to remove CO₂ from the atmosphere at a scale that leads to net negative emissions in the IPCC 1.5°C scenarios. Without CCS, scenarios suggest it becomes very difficult and expensive to reduce CO₂ emissions sufficiently fast to achieve global warming well below 2°C, stably, by 2100. This conclusion is in line with the Energy Transition Committee (ETC 2018) and McKinsey (2020). According to Peters and Sognnæs (2019), the median CCS deployment by 2050 ranges from 6 Gt CO₂/year to 13 Gt CO₂/year for scenarios that are Paris-compliant.

The United Nations Economic Commission for Europe (UNECE 2021) found in a brief that CCUS technology is an essential step towards mitigating climate change and key to unlocking the full decarbonisation potential in the energy, industry, and other and hard-to-abate sectors. The Technology Brief looks at the various technologies available to capture, use, and store CO₂. Political agreement is required for long-term engagement and societal commitment, recognizing the scale and cost of the industry that needs to develop in a very short time—billions (10⁹) of tonnes of CO₂ and trillions (10¹²) of dollars (US\$).

The world is set to reduce CO₂ emissions by 2030. However, it still aims to produce fossil fuels at a rate that is 120% more than would be consistent with limiting global warming to 1.5°C (UNEP 2020b). If the demand for fossil fuels is not reduced, CCUS seems even more necessary.

2.2.2. What does the IEA SDS mean for deployment of CCUS?

The 2017 CSLF TRM used an IEA scenario called 2DS (IEA 2017) to set targets for CO₂ stored by 2025 and 2035. More recently, the IEA (2020 a,b,c) introduced two new scenarios, the Stated Policies Scenario (STEPS) and the Sustainable Development Scenario (SDS) (see Box 2.1).

Table 2.1 compares the amount of CO₂ that needs to be captured by 2030 and 2050 in the SDS to the targets of the 2017 CSLF TRM; the SDS targets aim to achieve a temperature increase by 2100 that is 0.35°C lower. The IEA SDS scenario requires that almost 5.3 Gt CO₂ be captured and stored in the year 2050, with an additional 0.4 Gt CO₂ captured and used. This is lower than the lowest median of the IPCC scenarios (the median of all 90 models was about 10 Gt CO₂/year stored in 2050) but in line with the 2050 numbers in the Shell Sky Scenario (5.2 Gt CO₂/year) (Shell 2018). Equinor (2020) estimated in its Rebalance scenario, a scenario well below 2°C, that 2 Gt CO₂/year would have to be captured and stored in 2050.

Box 2.1. The IEA climate scenarios

The **Sustainable Development Scenario (SDS)** (IEA 2019a, 2020a,b,c) sets out the major changes that would be required to reach the three key energy-related sustainable development goals (SDGs) of the United Nations (UN) Sustainable Development Agenda (UN 2015; see also IEAGHG 2020a for more on interactions between CCS and the SDGs).

The trajectory for emissions in the SDS is consistent with reaching global net-zero CO₂ emissions in 2070. Maintaining net emissions at zero after this point would mean a 50% chance of limiting the global average temperature rise to 1.65°C above pre-industrial levels. If NETs are deployed after 2070 in the SDS, the temperature rise in 2100 could be limited to 1.5°C with a 50% probability.

The **Stated Policies Scenario (STEPS)** (IEA 2020a,b,c) incorporates today's policy intentions and targets, without trying to anticipate how these plans might change in the future. In this scenario, energy demand rises by 1% per year to 2040. The momentum behind clean energy technologies is not enough to offset the effects of an expanding global economy and growing population. The rise in emissions slows, but with no peak before 2040, the world falls far short of shared sustainability goals.

Table 2.1. Captured CO₂ in the IEA scenarios 2DS and SDS

Scenario	2030	2050
2°C scenario (2DS), IEA (2017)	1.168 Gt CO ₂ /year	5.514 Gt CO ₂ /year
Sustainable Development Scenario (SDS), IEA (2020 a,b,c)	0.840 Gt CO ₂ /year, of which 0.189 Gt CO ₂ /year is used	5.635Gt CO ₂ /year, of which 0.369 Gt CO ₂ /year is used

Thus, in the short term (2030), the IEA SDS target is less ambitious than the CSLF target in the 2017 TRM, but in the longer term (2050), the targets are, for all practical purposes, the same.

The IEA describes measures to reduce CO₂ emissions in the SDS (2020b) in more detail than is available for most other scenarios. This makes the SDS a good choice for setting targets in a consistent way.

Recommendation

Based on the IEA SDS, the following levels indicate where CCUS deployment should be:

- By 2030: Isolation from the atmosphere via CO₂ capture and storage should have increased by a factor of 10–15 from the 2020 level of 40 megatonnes (Mt) CO₂ per year.
- By 2050: Isolation from the atmosphere via CO₂ capture and storage should have increased by a factor of 100 or more from the 2020 level of 40 Mt CO₂ per year.

There will be regional differences in the need for deployment of CCUS, as pointed out in the IEA's *World Energy Outlook 2020* (2020c).

2.2.3. CCUS in industry and other sectors

Figure 2.2 shows how different measures may contribute to the cumulative reduction of CO₂ emissions in the IEA SDS. CCUS will account for approximately 4%, 12%, and 15% of the cumulative reduction of CO₂ emissions by 2030, 2050, and 2070, respectively (IEA 2020a,b).

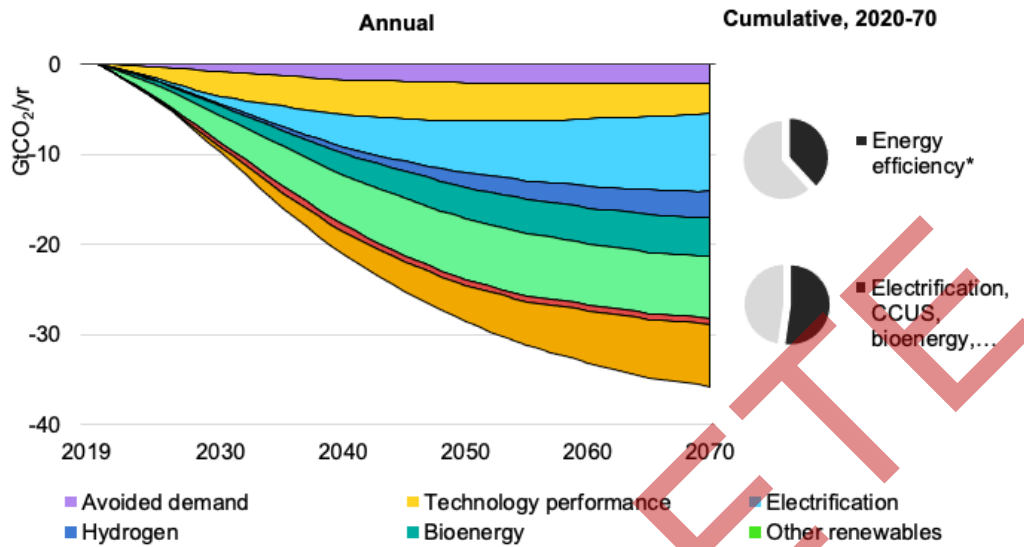
Major reductions must be made in all sectors. In the SDS, net CO₂ emissions will have to be reduced to 26.7 Gt CO₂/year in 2030, to 10 Gt CO₂/year in 2050, and to 0 Gt CO₂/year in 2070. Also in 2070, negative emissions from bioenergy with CCS (BECCS) will have to compensate for approximately 3 Gt CO₂/year of unabated emissions, and direct air capture (DAC) will have to compensate for a smaller amount (EA 2020b).

Tables 2.2 and 2.3 break down the CO₂ captured by source and sector (IEA 2020b).

Table 2.2. Global CO₂ (in Mt CO₂/year) captured, stored, and used in the SDS, by source (based on IEA 2020b) (Mt = million metric tons)

Source	2030	2050	2070	Cumulative to 2070
Fossil fuels	437	3 583	5 584	142 648
Industrial processes	312	979	1 073	36 562
Biomass/BECCS	81	955	3 010	52 257
Direct air capture	11	117	741	8 788

Total captured	840	5 635	10 409	240 255
Amount stored	650	5 266	9 533	220 845
Amount used	189	369	877	19 409



* Energy efficiency includes enhanced technology performance as well as shifts in end-use sectors from more energy-intensive to less energy-intensive products (including through fuel shifts).
Notes: CCUS = carbon capture, utilisation and storage. See IEA (2020a) and the ETP model documentation for the definition of each abatement measure. Hydrogen includes low-carbon hydrogen and hydrogen-derived fuels such as ammonia.

Figure 2.2. CO₂ reductions per year by measure in the SDS (IEA 2020b)

Table 2.3. Global CO₂ (in Mt CO₂/year) captured, stored, and used in the SDS, by sector (based on IEA 2020b)

Sector	2030	2050	2070	Cumulative to 2070
Industry	453	2 038	2 724	77 092
Power	223	1 877	4 050	87 529
Other fuel transformation	153	1 603	2 895	66 846
CO ₂ removal	76	821	2 920	47 739
Amount removed by BECCS	75	802	2 649	45 000
Amount removed by DAC	1	19	271	2 739

Industry is a hard-to-abate sector, with high energy intensity of industrial processes, long lifetimes and, in the short to medium term, a lack of viable low-carbon alternatives to the processes (ETC 2018a,b; CSLF 2019a). In 2019, the direct CO₂ emissions⁹ from industry were almost 9 Mt CO₂/year, or 23% of all CO₂ emissions. In the SDS, the industry sector will have to cut CO₂ emissions by 1 Gt CO₂/year by 2030, by 5 Gt CO₂/year by 2050, and by 8 Gt CO₂/year by 2070. In this sector, CCUS will have to contribute nearly 40% of accumulated reduction until 2070. For the cement industry, the percentage is

⁹ Direct emissions include energy-related and process emissions but exclude emissions connected to imported power and heat.

more than 60%. The reduction in industry will be from CCUS applied to processes (Table 2.2) and from the use of fossil fuels or fuel change, including hydrogen from fossil fuels with CCUS.

In the SDS, the power sector will be responsible for around 40% of the cumulative CO₂ reductions, with about half of that related to bioenergy (IEA 2020b).

CO₂ emissions from existing energy assets are estimated to generate 600 Gt CO₂ between 2019 and 2050. CCUS will be an important option in some cases to avoid the economic costs of early retirements (IEA 2020b).

CCUS will be responsible for more 90% of the cumulative CO₂ emissions reduction in fuel transformation (IEA 2020a). About 30% of the reductions will be from production of hydrogen and ammonia from fossil fuels and CO₂ captured from biofuel plants, contributing to reductions in the transport sector.

2.2.4. Negative emissions in climate scenarios

The IPCC (2014; 2018) highlighted the central role that technologies that remove CO₂ from the atmosphere will need to play in meeting ambitious climate targets. CO₂ removal technologies are described in Section 3.5. Tables 2.2 and 2.3 show that BECCS is expected to be the dominant negative emissions factor in the SDS. As pointed out by the IEA (2020b, referring to Huppmann et al. 2018), BECCS and DAC play a less important role in the SDS than in the IPCC 1.5°C scenarios.

2.3. The urgent need to increase the pace of CCS deployment

CCUS is proven and well understood. The separation of CO₂ from gas in streams and its use for EOR goes back many years. Anthropogenic CO₂ was first injected underground for storage in commercial-scale operations in 1996. Since then, more than 260 Mt of anthropogenic CO₂ emissions have been captured and stored, for use in either EOR or dedicated storage in saline aquifers (GCCSI 2019). By 2020, the global capture and storage capacity of projects currently operating, in 26 CCUS facilities around the globe, stood at around 40 Mt CO₂/year (GCCSI 2020a)¹⁰.

Judging from the annual status report on CCS from the Global CCS Institute (GCCSI 2020a), projects in advanced development will double the capture and storage capacity between 2020 and 2025, i.e., adding another 35–40 Mt CO₂/year. If all projects under consideration or planning in late 2020 were to come online over the next decade or so, the global CO₂ capture capacity will be 110–130 Mt CO₂/year (IEA 2020b; GCCSI 2020a), still far below the target of 650 Mt CO₂/year captured and stored by 2030, as indicated by the SDS (IEA 2020b). If the hubs described in Section 3.2.2 materialise, this number (110–130 Mt CO₂/year) may more than double.

The urgency of increasing the deployment rate of CCUS

Capturing and storing 650 Mt CO₂/year by 2030 requires a considerable acceleration of deployment of CCS projects. For example, storing 650 Mt CO₂/year will require that around 200–300 sites be developed between 2021 and 2030, assuming an average storage capacity of 2–3 Mt CO₂/year per site.

For large-scale CCS deployment to take place, it is necessary to move from project-by-project thinking to systems thinking. The momentum for deploying CCS appears to be on the rise.

With renewed national commitments and strengthened policy settings, which will be essential, it may still be possible to achieve the deployment needed.

¹⁰ In its *Global Status 2020*, GCCSI changed some of its definitions, and commercial-scale projects in operation now include six that were earlier classified as pilots or large-scale demonstration projects.

A review by the IEA Greenhouse Gas Research and Development Programme (IEAGHG 2017a) found that the rate of build-out in industry analogues has been comparable to the rates now needed, and that industry has historically achieved the rapid build-out rates required for the projected scale of deployment. However, the analogues have limitations, and substantial and perhaps unprecedented efforts from both the public and private sectors will be required to deliver and maintain the anticipated CCS build-out rates over the coming decades. These efforts will include market incentives, stable policy commitment, government leadership, and public support.

2.4. Strategic value of CCUS to the economy

CCUS offers the potential to reduce emissions in practically all parts of the global energy system. Achieving the needed reductions in CO₂ emissions without CCS is more costly than with CCS. Peters and Sognnæs (2019) show that in the four scenario runs that are specifically without CCS, the climate mitigation costs increase by a factor of 1.3–4.0. The Trade Unions Congress (TUC 2014) stated that CCS could save 40% of the cost of meeting a 50% global CO₂ reduction by 2050.

CCS is a driver of economic growth and employment in many ways:

- Making a decarbonised economy more competitive than one without CCUS (OGCI 2018, on the UK economy; SINTEF 2018, on the Norwegian economy).
- Generating economic value via job retention and creation (TUC 2014; GCCSI 2020b; Sintef 2018).
- Lowering energy bills (OGCI 2018, on the UK economy).
- Working with renewables to deliver reliable and stable power (IEAGHG 2017b).
- Enabling infrastructure re-use and deferral of decommissioning costs (GCCSI 2020b).
- Facilitating a just transition by alleviating geographic and timing mismatches (GCCSI, 2020b).
- Supporting economic growth through new net-zero industries and innovation spill overs (CSLF 2019a; GCCSI 2020b; IEA 2020c,d).

Several of the above statements have been corroborated by the UK CCUS Cost Challenge Task Force (2018), Element Energy (2018), and the UK Committee on Climate Change (2018).

3. Technology Needs

3.1. Capture

CCS is already happening in 26 large-scale commercial projects: eleven in natural gas processing facilities (excluding the Lost Cabin Gas Plant, which has temporarily closed down); four in fertilizer production; three in chemicals production (including one in ethanol and one in hydrogen); one in coal power production (excluding Petra Nova, which has suspended operations as a result of oil market conditions); and one in iron and steel production (GCCSI 2020a; IEA 2020b). In addition, there are several industrial cases in which captured CO₂ is used (AVR 2020; CRI n.d.; IEA 2020b).

3.1.1. Status power

Since the 2017 TRM, no new power projects have entered operation (GCCSI 2020a). However, according to GCCSI, seven power generation plants with CCS are expected to come online between 2021 and 2025+, all in the United States (2020a). Four are coal-fired, with an expected total capacity to capture around 15 Mt CO₂/year. Three of the power projects are gas-fired and smaller, with a total capture capacity of 4–5 Mt CO₂/year. In January 2021, NET Power announced that construction of its zero-emission natural-gas power system will begin on four power plants¹¹. In the Pouakai Project in New Zealand, 8 Rivers Capital will use a NET Power plant to create 170 MW for a hydrogen and ammonia plant (GCCSI 2020a).

3.1.2. Status industry

There are several industrial plants in which CO₂ is captured as part of the commercial process (GCCSI 2016a). These are found in natural gas sweetening, refineries, fertilizer production, iron and steel production, coal gasification, and ethanol production from biomass. Five plants have been added to the list since the 2017 TRM: the Gorgon natural gas processing plant in Australia; the North West Redwater Partnership's Sturgeon refinery and the Agrium fertiliser plant, both in Canada; the Jilin oilfield CO₂ EOR project in China; and the Qatar liquified natural gas CCS plant. Total capture capacity of the recently added facilities is 7.7–8.0 Mt CO₂/year.

Commercial facilities that have passed the final investment decision (FID) and are in the detailed engineering or construction phase include the HeidelbergCement Norcem plant, Brevik, Norway; the Yanchang Integrated CCS project, Shaanxi Province, China; and the ZERO waste-to-energy plant in Texas, United States. Onsite testing of CO₂ capture for the cement and waste-to-energy industries has taken place in Norway (Gassnova 2020). The HeidelbergCement Norcem plant project and Fortum Oslo Varme's waste-to-energy plant project are part of the Longship project (MPE 2020) (see also Section 3.2.2).

Other demonstration of CO₂ capture units has taken place on a cement plant in China¹², as well as on waste incineration plants in Japan¹³ and the Netherlands¹⁴. Large cement manufacturers such as Heidelberg and LafargeHolcim are considering CCUS at various plants, using amines as well as alternative technologies¹⁵. There are also significant research and pilot projects involving cement¹⁵.

¹¹ <https://www.forbes.com/sites/jeffmcmahon/2021/01/08/net-power-ceo-announces-four-new-zero-emission-gas-plants-underway/?sh=8d6a209175b3>

¹² https://cleanenergysolutions.org/sites/default/files/documents/cementsector_webinar_21jan2021_slides_final_optimized.pdf

¹³ <https://www.toshiba-energy.com/en/thermal/topics/ccu.htm>.

¹⁴ <https://www.akersolutions.com/news/news-archive/2019/aker-solutions-signs-carbon-capture-contract-with-twence-in-the-netherlands/> and <https://projecten.topsectorenergie.nl/projecten/decipher-de-risking-co2-capture-at-pilot-scale-at-hvc-bioenergy-plant-in-alkmaar-00033258>

¹⁵ <https://www.sintef.no/projectweb/cemcap/>; <https://www.project-leilac.eu>; <http://www.cleanker.eu>

The Swedish company Preem is conducting tests with Aker Solutions mobile test unit at its refinery in Lysekil, Sweden.¹⁶

Another sign of progress is that several industrial capture projects are moving from demonstration to full scale and are planning to come online between 2021 and 2025+ (GCCSI 2020a) and add 11–13 Mt CO₂/year capture capacity.

A wide range of capture technologies for the production of steel, cement, chemicals, refining, hydrogen, natural gas, heavy oil, fertilizers, and waste-to-energy were described in, among others, Bellona's *An industry's guide to climate action* (2018), McKinsey's *Decarbonization of industrial sectors: The next frontier* (2018), and CSLF's *Carbon Capture, Utilisation and Storage (CCUS) and Energy Intensive Industries (EIs)* (2019a). The latter found that capture technologies exist for many industrial applications and that:

- Energy-intensive industries (EIs) are taking various routes to reduce CO₂ emissions. In particular, some process-related emissions in EIs will be more difficult to eliminate if carbon capture is not considered.
- As one of several options, CCUS can be implemented quickly and has a key role to play.
- CCUS is capital-intensive and can present operational challenges; it needs support, incentives, and creative business models to stimulate widespread implementation at scale.
- CO₂ utilisation options can provide many EIs with a revenue stream to offset the costs of carbon capture.
- The cost impact of CCUS to the end user is modest, adding only a few percentage points to, for example, the cost of a new building or a new car.
- CCUS development requires strong commitments from different stakeholders.
- CO₂ utilisation can play an important role for business development and for raising the level of acceptability but will contribute little to the level of CO₂ mitigation needed.
- RD&D must be accelerated to drive down CCUS costs.

Other references on CO₂ emissions reductions for industry are ETC (2018a,b), Wyns et al. (2019), and IEA (2020b).

3.1.3. Status capture technologies

Technology readiness level (TRL) is a concept often used to assess the maturity of a technology. Arriving at a level where the technology is commercially available is not sufficient to describe its readiness to meet energy policy objectives (Adderley et al. 2016). To compensate for this, various solutions have been proposed. The IEA (2020a), for example, has proposed adding two more levels: TRL 10, in which the technology solution is commercially available but needs further integration efforts, and TRL11, in which the technology has reached predictable growth. ARENA (2014)¹⁷, on the other hand, has proposed using the Commercial Readiness Index (CRI) alongside TRLs to address the problem. While they were developed with the renewable energy market in mind, a technology's CRI can range in value from a hypothetical commercial proposition (CRI 1) to a "bankable" grade asset (CRI 6).

Reviews of capture technologies, including discussions of maturity in terms of TRL, can be found in a number of sources (Abanades et al. 2015; IEAGHG 2014 and 2019a; ZEP 2017a; CSLF 2015; Wood 2018; Concawe 2020¹⁸; IEA 2020b, and GCCSI (2021). It should be noted that capture technologies may be classified differently between the various reports, making direct comparison of TRL difficult.

¹⁶ <https://www.akersolutions.com/news/news-archive/2020/aker-solutions-starts-ccs-test-program-at-preem-refinery-in-sweden/>

¹⁷ <https://arena.gov.au/assets/2014/02/Commercial-Readiness-Index.pdf>

¹⁸ This report includes technologies with vendors and list of patents.

Leveraging large-scale facilities

Since the 2017 TRM was published, leveraging knowledge and experience from large-scale projects has taken place continuously through conferences and other meetings, including the CSLF Technical Group meetings. During the past six years alone, CSLF Technical Group meetings or workshops have included activities to leverage knowledge and experience from large-scale projects in the CSLF Recognized Projects portfolio¹⁹.

A recent report from Gassnova (2020) sums up what it considers to be the key learning points from the Longship project up to the FID. Although the project has been developed under circumstances that are unique for Norway, the experiences are relevant for the setup and development of other CCS projects. Other examples are documents from the projects Peterhead and White Rose in the United Kingdom.

More concrete knowledge-sharing has taken place through studies and papers produced by the International CCS Knowledge Centre (2019a,b) based on lessons learned from Boundary Dam Unit 3 (BD3). Reports by the Centre show that, for coal-fired power plants, the capital cost for capture on a per-tonne basis can be reduced by 69% from the BD3 facility to the Shand 300 MW single-unit power plant. Figure 3.1 shows how the learnings from the Boundary Dam project have been used in the planning of CCS for the Shand coal-fired power plant (CCS Knowledge Centre 2019a,b).

BD3 is a first-of-a-kind project at a full commercial scale. The project includes design features to allow for unrestricted operation of the power plant without CCS and contingencies in the size of CCS equipment, such as the volume of installed packing or space allowing for modifications. Future projects may not need these contingencies. For example, BD3 was not able to take advantage of some opportunities, but future projects would be able to apply these lessons. Mitsubishi Heavy Industries (MHI) has indicated similar cost savings for future plants based on the company's experience at Petra Nova.

Factors that contribute to cost reductions include:

- Seeking a larger CO₂ source requiring a large CO₂ capture facility that achieves better economies of scale.
- Optimizing the layout to reduce the lengths (and subsequently the costs) of interconnecting flue gas ducts and piping runs.
- Increasing the amount of modularization to make use of more efficient shop fabrication, resulting in reduced onsite construction costs.
- Increasing the percentage of the CO₂ captured, to maximize utilization of key components.
- Optimizing the integration of CCS with the host power plant to provide the thermal energy necessary for CCS at the lowest capital and operating cost.
- Utilizing both pilot and demonstration test results to mitigate risk premiums and equipment contingency requirements.
- Development of a CCUS supply chain, including suitable competition and standardization.
- Reducing amine (solvent) degradation, water consumption, and maintenance costs.

¹⁹ For more on CSLF Recognized Projects: <https://www.cslforum.org/cslf/Projects/Summaries>; for workshops: <https://www.cslforum.org/cslf/Events>; for examples, go to Technical Group meetings April 2019, October 2018, April 2018.

Capital Cost for CCS at BD3 vs. Shand

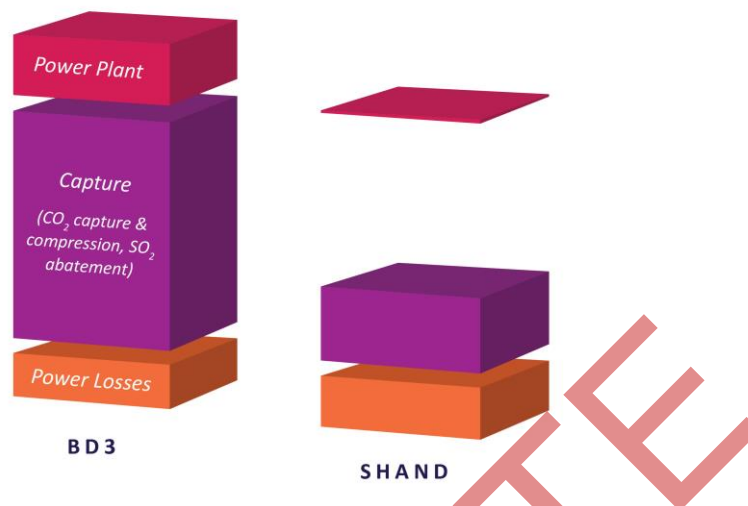


Figure 3.1. Cost reductions for the Shand Second-Generation CCS Facility Feasibility Study relative to costs of the BD3 CCS facility (International CCS Knowledge Centre 2018, all rights reserved)

Post-combustion flue gas is remarkably similar in cement production and in coal-fired power plants, and CCS lessons learned can be readily adapted and transferred across the industries. Lessons learned from both the BD3 CCS facility and the International CCS Knowledge Centre’s Shand study are currently being applied to CCS on cement at the Lehigh Cement production plant in Edmonton (feasibility study phase).

RD&D

The objective of RD&D in the field of CO₂ capture is make technologies more efficient and bring costs down. Capture costs have been reduced over the last decades, as shown by GCCSI (2019) and IEAGHG (2019a). The latter showed that benchmark capture cost has come down 22% and 15% for coal- and gas-fired power, respectively.

There is clear evidence of positive developments for improvements in capture technology. These include the following:

- The International Test Center Network (ITCN) has several new members.
- The CCUS R&D community and private partners are moving forward with commercial designs, some of which include second-generation carbon capture technologies.
- New capture technologies have been deployed and demonstrated:
 - NET Power has been demonstrating key components in the Allam Cycle in the company’s 50 MWth Demonstration Plant in La Porte, Texas.

Capture technologies currently classified as mature and commercial are based on chemical absorption or physical separation (Concawe 2020; IEA 2020b,c; IEAGHG 2019a; Wood 2018), membranes and physical solvents (Concawe 2020). Chemical absorption has been used commercially in chemical production and to purify natural gas and other gas streams in industrial settings for more than 80 years. It is the capture technology that has been used in the majority of CCS facilities through 2020, including power and industry (iron and steel) sectors. Membranes are in use in offshore Brazil to separate CO₂ from natural gas, and they are commercially available for CO₂ removal from syngas and biogas (IEA 2020b,c). Physical sorbent-based technology is used in industrial manufacturing processes, such as syngas, hydrogen, and natural gas cleaning (Concawe 2020).

IEAGHG compared the development of capture technologies between 2014 (IEAGHG 2014) and 2019 (IEAGHG 2019a). Chemical looping had moved from TRL 2 to TRL 5–6, but no larger-scale demonstration was planned. Some capture technologies, including catalysts (liquid absorbents) and temperature swing adsorption (solid sorbents), showed strong improvements from TRL 1 to TRL 6.

Several emerging technologies have commercial backing or have large-scale evaluation/demonstrations underway or planned, including some liquid absorbent technologies, solid absorbent technologies, membrane and hybrid membrane technologies, electrochemical separation technologies, and oxyfuel turbines. With the exception of high-temperature air separation membranes (TRL 4–7), none of these technologies were ranked higher than TRL 6. Chemical and calcium looping technologies were ranked at TRL 5–6, with pilots developed and operated. The more recent study by Concawe (2020) indicates that some solvents, membranes, and solid sorbents are at TRL 7–8.

IEAGHG (2019a) found that an electrochemical separation process, in which fuel cells are used to separate CO₂ from flue gas while at the same time producing power, had moved from TRL 1 to TRL 4 between 2014 and 2019, with significant potential for cost reduction. Wood (2018), Concawe (2020), and GCCSI (2021) ranked the fuel cell processes even higher, at TRL 5–7. Another electrochemically based technology, electrochemically mediated amine, in which electrolysis is used to regenerate the amine, has been ranked at TRL 2 (Concawe 2020) but could be higher (Wood 2018).

GCCSI (2019) shows that capture costs for facilities that plan to commence operation in 2024–2028 cluster around \$43/t CO₂ (USD). New technologies at pilot plant scale promise capture costs around \$33/t CO₂ (USD) (GCCSI 2019). Concawe (2020) gives similar future costs for technologies presently at TRL 5–8 and <5, respectively.

3.1.4. Hydrogen as a mechanism to decarbonise several sectors

Over the last decade, hydrogen has received attention as an attractive energy carrier for several purposes in transport, industry, power, and buildings (IEA 2020a,b,c):

- With the increased use of intermittent renewables in the power sector, energy storage has become a central issue. Hydrogen is an important alternative storage medium.
- Hydrogen has been assessed as a means to decarbonize cities and/or industrial sites, as hydrogen can be used for heat and power generation domestically and in industry, and as feedstock or to replace fossil fuels in processes:
 - In the United Kingdom, there are plans for several hydrogen networks, for example, H21, Hynet, ZeroCarbon Humber (H2H Saltend), H100 Fife, and Acorn. Other projects in planning or under consideration are H-vision – Port of Rotterdam and the Magnum hydrogen power plant, both the Netherlands; H2morrow in North Rhine–Westphalia, Germany; HYPOS East Germany in Germany; CCS Ravenna in Italy; Sines Green Hydrogen in Portugal; Advanced Clean Energy Storage in Utah, United States; and the Hydrogen Energy Supply Chain Pilot Project, which is a cooperation between Australia and Japan. For details, see Hydrogen Europe (2020) and ZEP (2021).
- Hydrogen is being studied for transport applications in which electrification is difficult, such as maritime, heavy-duty transport, and aviation.

The European Commission (EC 2020) and several nations have developed their own hydrogen strategies for the next couple of decades (e.g., Australia, Canada, France, Germany, Japan, the Netherlands, Norway, Portugal, South Korea, and the United States, with the United Kingdom in the process—see Annex B). General information on hydrogen production and applications can be found in Bellona (2020), CertifHy (Fraile et al. 2015), DNV·GL (2018), Energy Transition Commission (ETC 2018b), Hydrogen Council (2017), Hydrogen Europe (2020), IEA (2017, 2019b), Reigstad et al. (2019), and ZEP (2017b, 2021).

Present production and use of hydrogen

Hydrogen must be separated from other elements requiring externally supplied energy to produce pure hydrogen. It has a high energy density per unit mass but low energy density per unit volume in gaseous form.

Pure hydrogen can be produced from fossil fuels or by electrolysis (splitting water in hydrogen and oxygen by running electricity through the water). Using fossil fuels is currently the dominant method for dedicated production of pure hydrogen, mainly natural gas. This method produces CO₂ as an unavoidable by-product, unless it is combined with CCUS.

Hydrogen is also produced mixed with other gases as a “by-product” from facilities and processes designed primarily to produce something else.

In 2018, the demand for pure hydrogen was approximately 73 Mt, of which 38 Mt was used in the refining industry, 31 Mt for ammonia production, and 4 Mt in other parts of the chemicals industry and in the metals, electronics, food, and glass-making industries. Less than 0.01 Mt was directly used in the transport sector (IEA 2019b; International Renewable Energy Agency [IRENA] 2019). A few car manufacturers offer cars running on hydrogen. CO₂ emissions from dedicated hydrogen production were 0.8 Gt in 2019 (IEA 2020b). The demand for “by-product” hydrogen was 42 Mt in 2018, of which 12 Mt was used for methanol production and 4 Mt in the steel industry to produce direct reduced iron. The remaining 26 Mt was used in heating and for other purposes (IEA 2019b; IRENA 2019).

Potential future role of hydrogen

Projected hydrogen demand for 2050 varies from a factor of 4 to a factor of more than 10 over current production, as shown in Table 3.1. Figure 3.2 illustrates the distribution of hydrogen demand towards 2070, by sectors, in the IEA SDS.

Table 3.1. Hydrogen demand in 2050 by source/scenario

Source	Hydrogen demand, Mt H ₂ /year in 2050
IEA Energy Technology Perspectives 2020, SDS (IEA2020a)	287
DNV-GL 2020a	≈170
Energy Transition Commission 2018	425–650
Hydrogen Council 2017	550–650
Bloomberg 2020 (Climate Scenario)	801

Production methods: energy requirements, carbon footprints, and cost

All production of hydrogen involves some emissions of CO₂ in a lifecycle perspective. Some suggested definitions of clean (i.e., low, renewable, or sustainable) hydrogen are shown in Box 3.1.

There are several processes for producing hydrogen from fossil fuel or biomass feedstocks, all involving syngas production followed by separation of H₂ from CO₂ and storage of CO₂ (CSLF 2019a; de Valladares and Lucchese 2019; H21 2018; IEA 2019b; Voldsund et al. 2016; ZEP 2017b, 2021). The most common is steam methane reforming (SMR) of natural gas. Autothermal reforming (ATR) is in much less use than SMR but may become more economic than SMR for hydrogen production from natural gas with CCUS, depending on scale and application. Partial oxidation (POX) is also emerging as an alternative.

A commercially available alternative to production of hydrogen from fossil fuels with CCUS is water-splitting by electrolysis. This approach will reduce the associated GHG emissions only if the electricity is sufficiently low-carbon. The carbon footprint of renewables is in the 3–40+ kg CO₂/MWh range, lowest for wind and highest for photovoltaics (PV), stemming from production of construction material like concrete, steel, plastics, and the silica for PV cells.

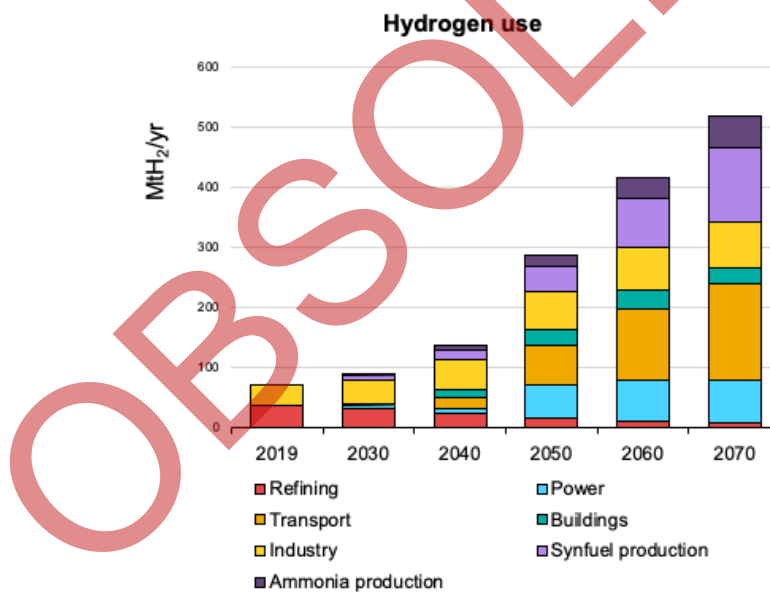
The CO₂ intensity of electricity must be below 170 g CO₂e/kWh for electrolysis to result in a smaller GHG footprint than hydrogen from SMR of natural gas without CCS, as seen in Figure 3.3, left panel (DNV-GL 2018; Eide 2019a). In Europe, only a handful of countries currently have an electricity mix well below this value.

To have the same carbon footprint as natural gas reforming with CCS, hydrogen production from electrolysis will have to come from an electricity mix with CO₂ intensity less than 20 g CO₂/MkWh (Figure 3.3, right panel.) In the IEA SDS, this will happen on a global scale after 2050 (IEA 2019a; IEA 2020a). Note, however, that there will be regional differences, that a few countries were already at this level in 2020, and that Europe and the United States are expected to reach this level in the 2040s.

Box 3.1: Definitions of clean hydrogen according to carbon footprint

- EU Taxonomy: To be classified as sustainable hydrogen, the emissions from hydrogen production must be below 5.8 kg CO₂/kg H₂ (100 kg CO₂/MWh for carbon footprint of electricity).
- CertifHy: The upper threshold for low-carbon hydrogen is 4.4 kg CO₂/kg H₂.
- EU Renewable Energy Directive II: To meet the renewable transport fuels of non-biological origin criteria, emissions must be below 3.384 kg CO₂/kg H₂.

Source: Hydrogen Europe 2020



Note: Ammonia production refers to fuel production for the shipping sector. Hydrogen use for industrial ammonia production is included within industry use.

Figure 3.2 Future hydrogen demand by sector

Source: IEA, Energy Technology Perspectives, 2020, <https://www.iea.org/reports/energy-technology-perspectives-2020>, all rights reserved

Some consequences of producing 287 Mt H₂/year (the estimate in 2050 from the SDS) are as follows:

- Producing 287 Mt H₂/year by electrolysis will require about 14,000 TWh electricity, which is more than 60% of current global generation and 33%–35% of that expected in 2050²⁰.

²⁰ Interpolated from data on the SDS in IEA 2020a, supported by information in <https://www.statista.com/statistics/238610/projected-world-electricity-generation-by-energy-source>

- Were 287 Mt hydrogen to be produced from steam reforming of natural gas with CCS, the consumption would be 30%–35% of current natural gas production.
- If 287 Mt H₂/year (9,500 TWh energy content) replaced unabated natural gas with the same efficiency, then the CO₂ emissions would be reduced by roughly 2 Gt/year.

The numbers show that:

- Both hydrogen produced from renewable electricity and hydrogen produced from natural gas with CCUS will be needed in the future. Figure 3.4 shows that in the SDS, hydrogen production from the two methods will be almost equal (IEA 2020a).
- Use of low-carbon hydrogen to replace fossil fuels will lead to significant reductions of CO₂ emissions, particularly in hard-to-abate sectors.

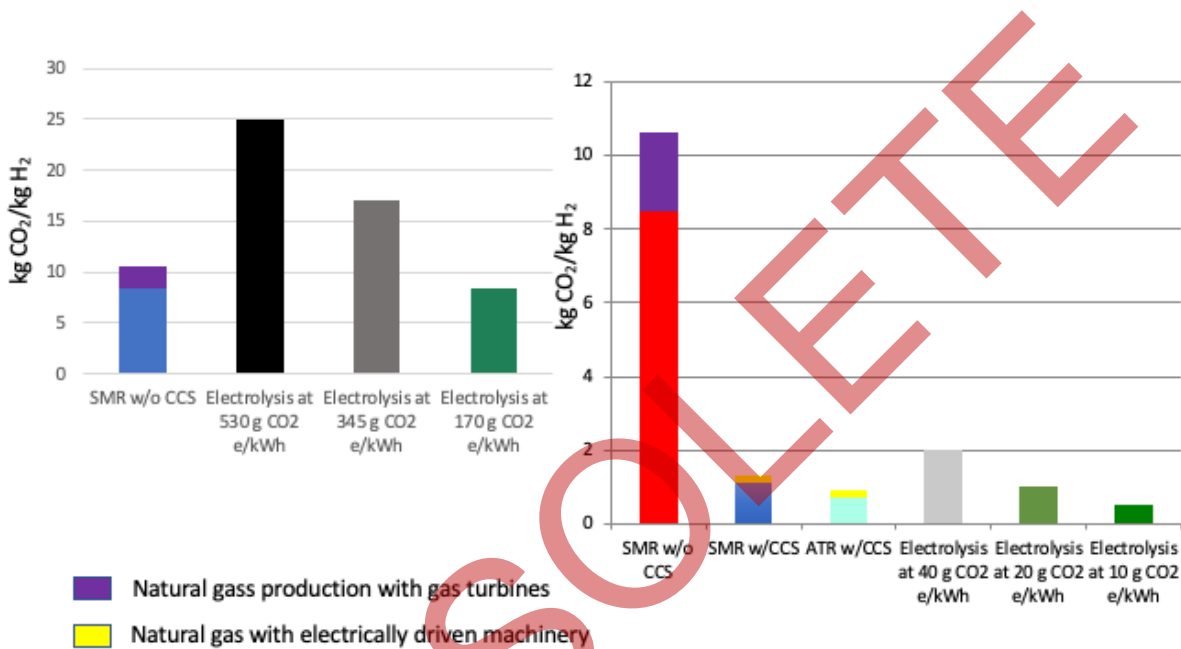


Figure 3.3. The carbon footprint of alternative ways to produce hydrogen. The world average carbon footprint for electricity generation is around 470 kg CO₂e/kWh²¹, and the European carbon footprint is around 270 g CO₂e/kWh²². Normal natural gas production means gas-driven turbines and compressors.

Figure 3.4 is in line with DNV·GL’s *Energy Transition Outlook 2020* (2020a), which suggests that the SMR with CCS route will dominate hydrogen production until after 2040. (See also DNV·GL 2018; H21 2018; Reigstad et al. 2019; Størset 2019; van Cappellen et al. 2019; ZEP 2021). On a longer timescale, photoelectrochemical and solar thermochemical may emerge (de Valladares and Lucchese 2019).

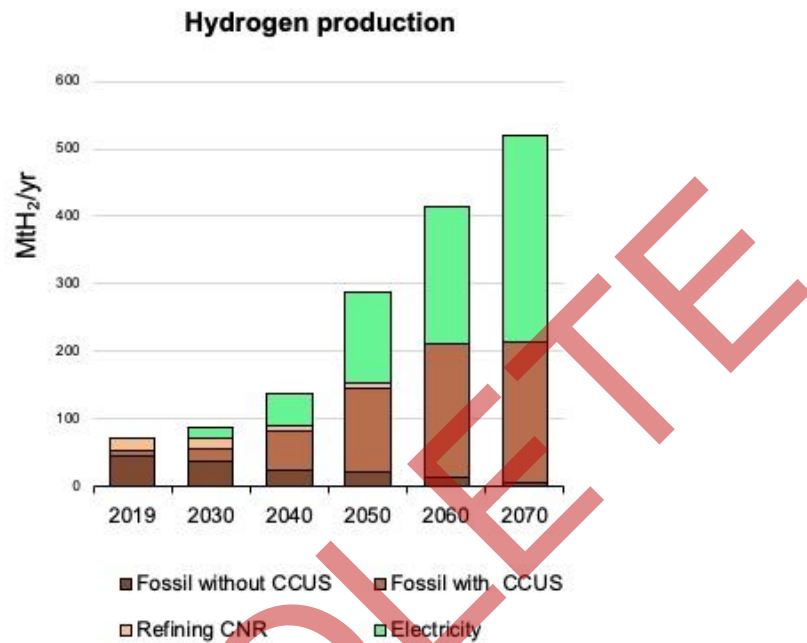
The footprint of renewable electricity is expected to come down as the materials become decarbonised (Pehl et al. 2017), but SMR may also get a reduced carbon footprint if the capture technology gets more efficient and the capture rate gets closer to 100%, compared to the more common 90% of today.

Thus, hydrogen produced from natural gas with CCUS meets all the requirements for clean hydrogen, as defined in Box 3.1.

²¹ <https://www.iea.org/reports/global-energy-co2-status-report-2019/emissions>

²² <https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-3/assessment>

The cost of low-carbon hydrogen produced from SMR with CCS is expected to stay in the range of 1–2 €/kg H₂ between 2019 and 2050 (IEA 2020 a,b; ZEP 2017b). The cost of hydrogen from electrolysis in 2019 was in the range of 3–7 €/kg H₂ but expected to come down to the range of hydrogen from fossil fuels with CCUS by 2050 (IEA 2020 a,b; ZEP 2017b). Sales of the by-product oxygen may contribute to lowering the cost. The crossover of costs for the two options may happen between 2035 and 2050, according to ZEP (2017b). However, the time for crossover cost is regionally dependent.



Note: Refining CNR refers to the production of hydrogen as a by-product of catalytic naphtha reforming in refineries

Figure 3.4. Hydrogen production from fossil fuels with and without CCS in 2030 and 2050 in the SDS. Source: IEA, Energy Technology Perspectives, 2020, <https://www.iea.org/reports/energy-technology-perspectives-2020>, all rights reserved.

Hydrogen from electrolysis using electricity from wind will require a much larger land area than hydrogen produced from fossil fuels with CCUS. To produce 12.5 TWh/year of hydrogen will require 0.008 km² for hydrogen from natural gas with CCUS and 460.5 km² for hydrogen from wind, of which 0.5 km² would be for the electrolyzers (ZEP 2021).

Examples of hydrogen production from fossil fuels with CCUS

Several plants are presently capturing CO₂ from hydrogen production. Some use the CO₂ for EOR (examples are Port Arthur in Texas, USA; the Northwest Sturgeon Refinery in Alberta, Canada; and four fertiliser plants), some inject in saline aquifers (examples are Quest in Alberta, Canada; Tomokomai in Japan; and Erdos in Xinjiang, China), and some export the CO₂ to the food or petrochemical industries (examples are Sinopec Maoming Petrochemical Company and Lihuyi Group Co, Ltd., both in China, and fertiliser producer Yara in Norway). Additionally, there are efforts underway in the United States that couple co-feeding of coal, biomass, and waste plastics with CCUS to drive towards zero- or negative-emissions hydrogen.

Technology needs and improvements

The examples above show that hydrogen production from fossil fuels with CCUS is happening and that the technology works. However, continued research, development, and innovation for improved emerging and low-cost technologies for clean hydrogen production must be encouraged.

Several of the topics listed below were addressed in the Accelerating CCS Technologies (ACT) project ELEGANCY²³, and improvements were achieved.

Hydrogen from fossil fuels and biomass with CCUS

- Expand the use of alternatives to SMR in hydrogen production from fossil fuels or biomass with CCUS.
- Increase capture rates.
- Improve the reforming process (an example of technologies under development is the EU project HYPER²⁴).
- Process intensification and new technologies—more compact, efficient, and economic solutions, such as:
 - Membranes (an example of technologies under development is a single-stage reformer process using protonic membranes [Malerød-Fjeld et al. 2017])
 - Concentrated solar energy to create heat for the reforming process
 - Pyrolytic, electrochemical, or thermochemical splitting of methane to create hydrogen and solid carbon (carbon black)
 - Technologies for catalytic reforming of the fuel and separation of H₂ and CO₂
- Process integration in the co-production of H₂ and, for example:
 - Electricity and heat production
 - In industrial processes where H₂ or H₂-enriched natural gas can replace fossil-fuel-based feedstock

Hydrogen in general

- **Hydrogen infrastructure.** A limiting factor to large-scale deployment of hydrogen produced from fossil fuels with CCUS is that presently there is no large-scale CO₂ transport and storage infrastructure in place. Several of the CCS hubs described in Section 3.2.2 involve hydrogen production and transport. Infrastructure for both CO₂ and H₂ is a critical enabler for hydrogen to play the envisaged role in the low-carbon economy. There is limited experience with hydrogen pipelines, but there seems to be optimism regarding re-use of natural gas pipelines. Studies on hydrogen infrastructure are underway (DNV·GL webinar November 04, 2020²⁵; ZEP 2021) and need to be followed up.
- **CO₂ infrastructure.** Open-access CO₂ transport systems and storage sites must be available for short-term deployment of hydrogen produced from natural gas with CCUS. This also applies to hydrogen produced from electrolysis when the hydrogen is to be used, for example, to produce synthetic fuels.
- **Safety.** Safety is always a concern. There is long-term experience from handling hydrogen in refineries and ammonia plants but much less regarding its long-distance transport and its use in other sectors, including the domestic and transport sectors. Research on safety aspects of hydrogen in these sectors is ongoing in the United Kingdom and the Netherlands (DNV·GL webinar November 04, 2020²¹).
- **Creating a market and business models for hydrogen.** Incentives are needed to scale up production and establish a market for hydrogen, such as stimulating commercial demand for clean hydrogen, addressing the investment risks of first movers, eliminating unnecessary regulatory barriers, and harmonising standards (IEA 2019b).

²³ <https://www.sintef.no/projectweb/elegancy/>

²⁴ <https://hyperh2.co.uk>

²⁵ <https://www.dnv.com/oilgas/webinars/developing-efficient-hydrogen-infrastructure-noindex.html>

Summary: Hydrogen production from natural gas with CCUS

- Hydrogen produced from renewable electricity and from natural gas with CCUS will both be needed.
- Hydrogen produced from natural gas with CCUS meets hydrogen emission benchmarks set by EU and Certifhy.
- Hydrogen produced from natural gas with CCUS may have a lower cost and carbon footprint than hydrogen produced from electrolysis until after 2040 but with some regional dependence.
- Production of hydrogen from fossil fuels with CCUS can be deployed immediately and does not need to wait for low-carbon electricity, thus forming a bridging solution to truly green hydrogen.
- Hydrogen produced from natural gas with CCUS can be installed at existing hydrogen plants.
- RD&D will contribute to more efficient and cheaper hydrogen production from fossil fuels with CCUS.
- Use of low-carbon hydrogen to replace fossil fuels will lead to significant reductions of CO₂ emissions in hard-to-abate sectors such as industry and transport.
- Introducing hydrogen produced from natural gas with CCUS now will kick-start the transition to global and regional supply chains for hydrogen and provide much-needed experience.

Recommendations: Hydrogen production from natural gas with CCUS

- Improve and optimise hydrogen production from fossil fuels with CCUS. New reforming processes and process intensification, e.g., using membranes, will lead to efficiency increase and cost reductions.
- Hydrogen and CO₂ infrastructure must be in place, including production, transport, and storage.
- Safety aspects must be addressed.
- Incentives must be introduced to create a market for hydrogen.

3.1.5. Digital and other enabling technologies

Diverse technologies, platforms, and innovations developed outside of the energy sector are now being brought to this sector to reduce costs, risks, and timescales for projects and could be applicable to current and future CCS projects as well. The deployment of CCS currently falls short of the projected capacity needed to achieve global emissions reduction targets, despite being a proven technology in the reduction of GHG emissions.

A wide range of relevant applications for digital and enabling technologies is now appearing. These applications could potentially benefit CCS by reducing costs and addressing risks and challenges in deployment. IEAGHG (2020b) provided a high-level assessment of some such technologies, including:

- Robotics, drones, and autonomous systems
- Novel sensors
- Digital innovations
- Virtual/augmented reality (VR/AR)
- Additive manufacturing
- Advanced materials

Although only some applications are currently under development in CCS, the benefits of these technologies discussed in the report are largely transferable from related sectors.

IEAGHG (2020b) assessed potential global cost savings benefits in light of the deployment trajectory of the IEA 2DS. The results are shown in Figure 3.5.

More than half of the total savings are due to digital innovations and their applications, with VR/AR in second place. The total cumulative global savings may be as much as \$200 billion (USD) in total lifetime costs of projects deployed up to and including 2040, which is a savings of 10% of the counterfactual investment cost. Of this, 8% would be saved in capital expenses, 27% is estimated to be saved in operating expenses, 47% would be saved because of carbon costs of downtime and leakage, and 13% of the savings are estimated in transport and storage (of which 96% is saved in storage projects).

Applications of artificial intelligence and the Internet of Things in predictive maintenance and automation will deliver the greatest potential reductions in project costs. Additive manufacturing will have the greatest impact in capture downtime. VR (virtual reality) and AR (augmented reality) will have primarily impact on the reduced downtime, while advanced materials are considered most applicable in storage projects.

It must be noted that significant savings are expected to be realised only from 2030, but these will clearly be beneficial to the CCS industry. The figure below shows the spread in projected savings by each emerging technology group; over half of these savings are due to digital innovations and their applications.

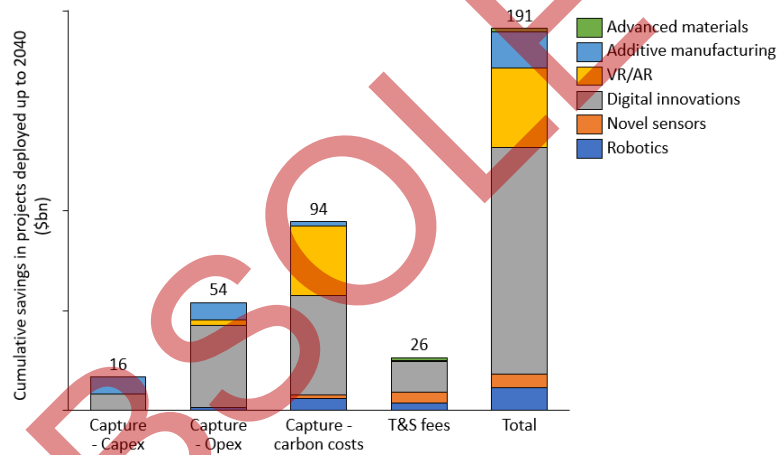


Figure 3.5. Distribution of global cost savings (%) in total lifetime costs of projects deployed up to and including 2040, sorted by emerging technology group (courtesy of IEAGHG 2020b)

3.1.6. Technology needs capture

Areas where technology development are needed include (MI 2018):

- Liquid absorbents:
 - **Designing high-performing solvents for CO₂ capture.** Obtaining more accurate thermodynamics and mass transfer models should be fundamental objectives, in order to increase the ability to predict and control the chemical and physical properties of liquid absorbents. Interaction with the chemical industry is necessary.
 - **Creating environmentally friendly solvent processes for CO₂ capture.** This should involve degradation aspects, development of models that allow reliable prediction of loss, and mitigation strategies.
- Sorbent materials and looping processes:
 - **Designing tailor-made sorbent materials.** Objectives are developing sorbent materials that lower the energy penalty and equipment costs by enhancing long-term reactivity, recyclability, and robust properties of materials.

- **Integrating sorbent materials and processes.** This should address topics of importance to chemical (and other) looping technologies, such as novel reactor and cycle designs.
- Membranes:
 - **Understanding transport phenomena in membrane materials.** Research should include predictive models linking membrane structure and transport mechanisms to the needed separation properties.
 - **Designing membrane system architectures.** The challenge is to improve the processing of membrane materials and support substructure/morphology for large-scale manufacturing.
- Combustion and hydrogen:
 - **Catapulting combustion into the future.** Fundamental research is needed to develop understanding of processes in high-intensity pressurised combustion.
 - **Producing hydrogen from fossil fuels with CO₂ capture.** Research areas include microchannel combustion, reforming catalysts, novel reactor design, and high-temperature convective reforming.

RD&D activities should include efforts to bring these low-TRL technologies (TRL 1–4) to higher levels.

Other activities should include:

- Further work looking at the cost–benefit analysis for each of the emerging and enabling technologies
- Further exploration and development of promising technologies at TRL >5, including looping and other sorbent processes, polymeric membranes, temperature swing adsorption, adsorption using catalysts, and fuel-cell-based electrochemical processes
- Stronger modularization of the capture units
- Improvements in and more verification data for advanced computational tools
- Advanced manufacturing techniques, such as 3-D printing
- Exploring and exploiting the benefits of hybrid solutions
- Materials research, development, and testing
- Reduced environmental impacts of capture technologies (for amine-based technologies, significant improvements have been made regarding degradation and emissions)
- Air separation and combustion technologies
- Parametric design to allow scaling from the large pilot scale to commercial applications
- Optimized overall process, system integration, and process simplification
- International cooperation to build more test facilities that can bring capture technologies from laboratory or small pilots to large pilots and small demonstrations (e.g., build on the ITCN and the European Carbon Dioxide Capture and Storage Laboratories [ECCSEL])

3.1.7. Conclusions and recommendations for CO₂ capture

- Knowledge transfer from completed large-scale facilities have led to reduced costs for subsequent plants.
- RD&D has led to reduced capture costs.
- Capture technology is commercial but so far limited to chemical liquid absorption.
- No technologies have passed TRL 6 with documented evidence of significant cost reductions in the last five years.
- Hydrogen from fossil fuels, in particular natural gas with CCUS, will, at least regionally, be climate- and cost-competitive with green hydrogen for the next two decades, contingent on available storage sites for CO₂.

Suggested priority actions for capture:**Toward 2025:**

- Bring to demonstration (TRL >7) CO₂ technologies for power generation and industrial applications that were at TRL 5–7 in 2020.

Toward 2030:

- Bring to commercialisation (TRL ≥9) CO₂ capture technologies for power generation and industrial applications that were at TRL 5–7 in 2020, with avoided cost in \$/t CO₂ at least 25% below that of 2020 commercial technologies (\$55/t CO₂ [USD]), while at the same time minimizing environmental impacts.
- Implement CCUS at 30% of fossil-fuel-based hydrogen production facilities.

Toward 2050:

- Bring to commercialisation (TRL ≥9) CO₂ capture technologies for power generation and industrial applications that capture very close to 100% of the CO₂ and, at the same time, achieve at least 40% reduction of avoided carbon cost in \$/tCO₂ compared to 2020 commercial technologies, while minimizing environmental impacts.
- Cover 50% of the global hydrogen demand by production from fossil fuels with CCS.

Note: There are two actions that will contribute to cost reductions of CO₂ capture but that are not treated here:

- Combinations between CCS and renewable energy (wind, solar, geothermal, hydropower, or other renewables) to supply the energy for the capture process
- Economy of scale for projects and in markets

3.2. Transport and infrastructure

CSLF status reports on global network infrastructures (CSLF 2020b) defined CO₂ industrial clusters, networks, and hubs by slightly modified versions of definitions in GCCSI (2016b). However, these definitions have not achieved universal acceptance. This TRM uses the definition suggested by IEA (2020b):

CCUS hubs are industrial centres with shared CO₂ transport and storage infrastructure.

Thus, the concept “hubs” consists of one or more industrial centres, or clusters, a transport system, and one or more common storage sites.

3.2.1. Transport

CO₂ is being transported daily by pipelines, trucks, trains, and ships in many parts of the world, although by the last three in limited amounts.

Pipelines

Pipelines are the most common method for transporting the large quantities of CO₂ involved in CCUS projects. In the United States, more than 7,600 kilometres (km) of onshore pipelines transport around 70 Mt CO₂/year (GCCSI 2016b; IEA 2020b; NETL 2015), and another 720 km in Canada transport around 6 Mt CO₂/year. Other onshore CO₂ pipelines are operating in the Netherlands, United Arab Emirates, and Saudi Arabia. Except for the Denbury Gulf Coast CO₂ Pipeline²⁶, there is limited experience with CO₂ pipelines through heavily populated areas, and the 153 km, eight-inch pipeline

²⁶ <https://www.denbury.com/operations/gulf-coast-region/Pipelines/default.aspx>

that serves Snøhvit, Norway, is the only offshore CO₂ pipeline. The ISO has issued an international standard that, at an overall level, points out what is distinctive to CO₂ pipelines relative to other pipelines (ISO 2016). There are also guidelines and recommended practices on CO₂ pipelines (e.g., DNC 2021).

While extensive experience with CO₂ pipelines exists, RD&D can contribute to optimizing the systems, thereby increasing operational reliability and reducing costs:

- In areas with existing oil and gas pipelines, there is potential to reuse or repurpose them for transport of CO₂, thus reducing the cost of developing a new infrastructure. The investment needed for such a conversion may be less than 10% of building a new one (Acorn 2020)²⁷. The Acorn CCS project in the United Kingdom and the Queensland Carbon Hub/Carbon Transport and Storage Company (CTSCo) in Australia are examples of projects that propose reuse of existing pipelines (IEA 2020b).
- Improved understanding and modelling of properties and the behaviour of CO₂ rich streams, including two-phase flow, validated flow assurance tools, thermophysical property models, and CO₂ from different sources.
- The impact of impurities on compression work and on pipeline materials (some of these topics were addressed in IEAGHG 2016).
- Improved fracture control, leakage detection, improved capabilities to model releases from pipelines.
- Identification and qualification of materials or material combinations that will reduce capital and/or operational costs.
- Effective and accepted safety measures for large supercritical pipelines, particularly in more populated areas, and public outreach and stakeholder dialogue and communication.
- Integrating low-pressure pipeline networks with high-pressure pipeline systems.
- Standardisation for quantification (including metering) and verification.

In addition to these topics and challenges, ZEP (2020) also mentions that accurate mass flow metering is critical in CCUS cluster networks to ensure appropriate allocation of costs and flows between sources and the storage site.

There are currently no commonly agreed-on specifications for the quality of the CO₂ to be transported and injected, which leads to uncertainty regarding transport of CO₂ containing impurities (ISO 2016b). A strict CO₂ specification gives little flexibility in a CO₂ transport network and will add to the cost. It seems necessary that CO₂ specifications will be identified and documented for each case. However, in the absence of such specifications, different national approaches may apply in case of transnational transport of CO₂. This may cause discussions (ZEP 2020), hence the need for internationally recognised standards that are performance-based rather than prescriptive.

Ship transport

Ship transport can be an alternative to pipelines in a number of regions, especially in cases where CO₂ from several medium-sized (near-) coastal emissions sources need to be transported to a common injection site or to a collection hub for further transport in a trunk pipeline to offshore storage. Shipment of food-quality CO₂ already takes place on a small scale (1,000–2,000 cubic metres per ship) across the North Sea. Several studies have concluded that CO₂ transport by ship of larger volumes is feasible (CSLF TRM 2017). ZEP (2020) gives a condensed summary of aspects of ship transport of CO₂ and concludes that it is proven and feasible.

IEAGHG (2020c) compared different scenario options, including direct shipment to a hypothetical offshore location, offloading CO₂ into a temporary facility prior to injection and shipment to an intermediate onshore location, and then transfer by pipeline to a hypothetical offshore storage

²⁷ <https://actacorn.eu/sites/default/files/ACT%20Acorn%20Pipeline%20Re-use%20Factsheet.pdf>

location. Ship transport may be a cost-effective solution to pipeline transport, but this depends on low flow rates and long distances.

A front-end engineering report for the full-scale industrial CCS project Longship (MPE 2020) in Norway confirmed that ships resembling fully pressurised liquified petroleum gas (LPG) vessels will be appropriate for the project, allowing the project to tap into existing ship construction markets (Equinor 2020)²⁸. The design of fully pressurised LPG vessel with minor modifications for CO₂ transport has allowed a path in which the International Association of Classification Society (IACS) DNV·GL (now DNV) provided a General Approval for Ship Application (GASA) statement confirming design approval in November 2019 (DNV·GL 2020b).

The Longship project will use loading and offloading of the CO₂ at shore. The feasibility studies did not identify major issues with this approach. Other major regional projects (see Section 3.2.2 on hubs) are also considering ship transport of CO₂. There is a need to ensure interoperability (between projects) of the ships, so that one ship can move between different sources and offloading ports/terminals without the need for modifications. This will require establishing codes, standards, and international regulations.

Offshore offloading of CO₂ is not proven, and no consensus exists for the most appropriate solution. Offshore unloading will lead to increased costs of offshore processing of CO₂ for injection during periods of unavailability due to weather conditions. As experience is limited, this option will need further engineering for optimization. More detailed discussion of offshore loading can be found in IEAGHG (2020c) and ALIGN-CCUS²⁹.

For short distances near shore and for transport on inland waters, barges may be an alternative solution to ships (van Hijfte 2020; CO2LOS II³⁰). The plan in the Netherlands is to load compressed CO₂ onto barges for transport and injection via platform to a geological formation below the seabed. A CO₂ source will be served by at least two barges to secure continuity. It is expected that construction of barges can start in 2021 and the system can be operational from 2023³¹.

International shipping emits a significant amount of CO₂, estimated to 1 Gt in 2018. To reduce the carbon footprint of a transportation chain including ship transport of CO₂, the emissions must be reduced. Ship-based carbon capture (SBCC) is seen as a cost-effective and short-term alternative to electrification and hydrogen. SBCC has been researched in projects in the Netherlands (DerisCO₂ and CO₂ASTS)^{32,33} as well as in CO2LOS II²⁶. It is also being addressed in the research project MEMCCSea³⁴, a project under the international partnership ACT³⁵. MHI announced in August 2020 that the company will build and test a carbon capture system for ships³⁶.

Other transportation means

The transport of smaller volumes of industrial and food-grade CO₂ has been successfully undertaken by truck and rail for more than 40 years. The cost of transportation is relatively high per tonne of CO₂ compared to pipelines, so truck and rail transport may have a limited role in CCS deployment, except

²⁸ The capacity of the selected ship design will be 7,500 m³, with design pressure of 19 barg and minimum tank design temperature of -35°C.

²⁹ <https://www.alignccus.eu/our-results/wp2-transport>

³⁰ <https://www.sintef.no/globalassets/sintef-industri/rapporter/co2los-ii-final-report--public.pdf>

³¹ <https://carboncollectors.nl/co2-transport-storage/>

³² <https://www.conoship.com/2020/09/21/ship-based-carbon-capture/>

³³ <https://www.conoship.com/wp-content/uploads/2020/06/200513-CO2ASTS-Public-Concise-Report.pdf>

³⁴ <http://www.act-ccs.eu/memccsea>

³⁵ <http://www.act-ccs.eu/memccsea>

³⁶ <https://www.euractiv.com/section/energy-environment/news/worlds-first-carbon-capture-at-sea-set-for-shipping-trials/>; <https://www.motorship.com/news101/ships-equipment/new-project-joins-the-race-for-the-first-onboard-co2-capture-installation/>; <https://www.hellenicshippingnews.com/mitsubishi-shipbuilding-to-test-worlds-first-marine-based-co2-capture-system/>

for small-scale CCS opportunities or pilot projects. Roussanaly et al. (2017) show that train-based transport of CO₂ may have site-specific cost benefits related to conditioning costs. For example, a Swiss study³⁷ found that for 100,000 tons of captured CO₂ in Switzerland, a combination of a liquid-CO₂ pipeline to a local loading station and a train to Rotterdam was the most realistic option. At larger scales, transport via pipeline is the only feasible option.

3.2.2. Hubs

There are several potential benefits of moving away from project-by-project thinking to systems thinking, i.e., developing hubs of from several sources (GCCSI 2016; ZEP 2013, 2020; and IEAGHG 2015):

- Cost-sharing
 - Lowering costs in building early infrastructure by utilizing benefits of connecting low-cost industrial sources with storage sites.
 - Distributing investment and operational costs by sharing infrastructure, i.e., the cost per unit CO₂ transported will be lowered.
- Lowering the entry barriers for participating CCS projects, such as emitters with small-volume sources and emitters with limited or no access to local storage.
- Securing sufficient and reliable CO₂ for CO₂-EOR and other CO₂ utilisation projects, which is likely to be an important element of some clusters because of the revenue it can contribute.
- Minimizing the environmental impacts associated with infrastructure development, as well as the impacts on communities.
- Minimizing and streamlining efforts in relation to planning and regulatory approvals, negotiations with landowners, and public consultations.
- Sharing and utilizing surplus heat in the capture processes of industrial clusters.

The importance of hubs can be highlighted by some quotes:

- “CCUS infrastructure is key to unlocking huge clean growth potential in the UK and can contribute to a cost-effective pathway for reducing UK CO₂ emissions” (UK CCUS Cost Challenge Taskforce 2018).
- “Build CO₂ networks and accelerate CO₂ storage assessments in key regions” (IEA 2018).
- “The report establishes that cross-border CO₂ transportation infrastructure has a major role to play in delivering a cost-efficient transition to a low-carbon economy” (ZEP 2020).

Four initiatives underscore the importance of hubs:

1. The Oil and Gas Climate Initiative (OGCI) KickStarter initiative is designed to unlock large-scale commercial investment in CCUS by enabling multiple low-carbon industrial hubs. These hubs capture CO₂ from several industrial companies and bring economies of scale by sharing transport and storage infrastructure. As of the beginning of 2021, the hubs included in the KickStarter initiative are Net Zero Teesside, UK; Northern Lights/Longship, Norway; Rotterdam (Porthos), the Netherlands; China Northwest, Xinjiang, China; Texas, USA; Louisiana, USA; and Edmonton, Canada (high-potential hub under evaluation).
2. EU Projects of common interest (PCIs) are key cross-border infrastructure projects that link the energy systems of EU countries. They are intended to help the EU achieve its energy policy and climate objectives: affordable, secure, and sustainable energy for all citizens, and the long-term decarbonisation of the economy in accordance with the Paris Agreement. The present PCI list includes five projects for cross-border CO₂ networks: Ervia Cork, Ireland; Port of Rotterdam (Porthos), the Netherlands; Acorn (CO₂ Sapling Transport and Infrastructure Project), UK; Northern Lights/Longship, Norway; and the Port of Amsterdam (Athos), the Netherlands.

³⁷ <https://www.suslab.ch/ms-ccs-feasibility>

3. The ALIGN-CCUS³⁸ project is an ACT project funded by the European Commission and led by the Netherlands. A strong focus of the transport work package is ship transport of CO₂. The industry clusters considered were North Rhine–Westphalia, Germany; Rotterdam, the Netherlands; Grenland, Norway; Oltenia, Romania; and Grangemouth and Teesside, United Kingdom.
4. The CarbonSAFE programme in the United States is an initiative formed to provide a better understanding of integrated storage project screening; site selection; characterization; baseline monitoring, verification, and accounting procedures; and information necessary to submit appropriate permit applications for such projects.

The projects in PCI and OGCI KickStarter are described with references in CSLF 2020b and ZEP 2020.

Operational and planned CO₂ hubs

Figure 3.6 shows hubs in operation and in planning as of end-2020. Three hubs—Denver City, Gulf Coast, and Rocky Mountains—are basically pipelines connecting natural reservoirs of CO₂ with oil fields where the CO₂ is used for EOR. They will not be discussed here, nor will they go into any estimates of hub capacities.

By the end of 2020, there were two operational hubs (offshore Brazil and onshore in Canada [ACTL]), one that passed the FID (Longship in Norway), and twenty in planning.

The ACTL came into operation in June 2020. It uses a 240-km-long high-pressure, open-access pipeline owned and operated by Wolf Midstream. The pipeline safely transports CO₂ from the North West Sturgeon Refinery and the Agrium Fertilizer Plant to aging oil reservoirs in Central Alberta for EOR and secure permanent storage. The ACTL is an expandable network built to support significant future emissions solutions and new utilisation pathways. The technology is well known from large-scale single-source projects.

The Petrobras Santos CCUS project separates natural gas and CO₂ on floating production storage and offloading (FPSO) units for injecting into oil reservoirs for EOR via seabed flowlines and subsea templates.

The Norwegian Longship project will take CO₂ from cement and waste-to-energy plants in southeast Norway (the waste-to-energy plant is pending an additional funding source) and transport it by ship to a terminal on the west coast, where it will be piped to an offshore storage site in the Aurora license in the North Sea (MPE 2020) (see Figure 3.7). The transport and storage part of Longship is also known as the Northern Lights project, which has negotiated potential future CO₂ volumes from industrial facilities or clusters along the coasts of Scandinavia and other northern European countries, as seen in Figure 3.7.

Of the other infrastructure projects in planning, the most advanced are probably Net Zero Teesside and Humber in the United Kingdom and Porthos in the Netherlands. The total capacity of the hubs in Figure 3.8 will exceed 240 Mt CO₂/year if all are built to the maximum planned capacity. This number includes some facilities that are also included in the 110–130 Mt CO₂/year mentioned in Sections 3.1.1 and 3.1.2. All of the 20 planned hubs may not materialise, but more will probably come on the drawing board.

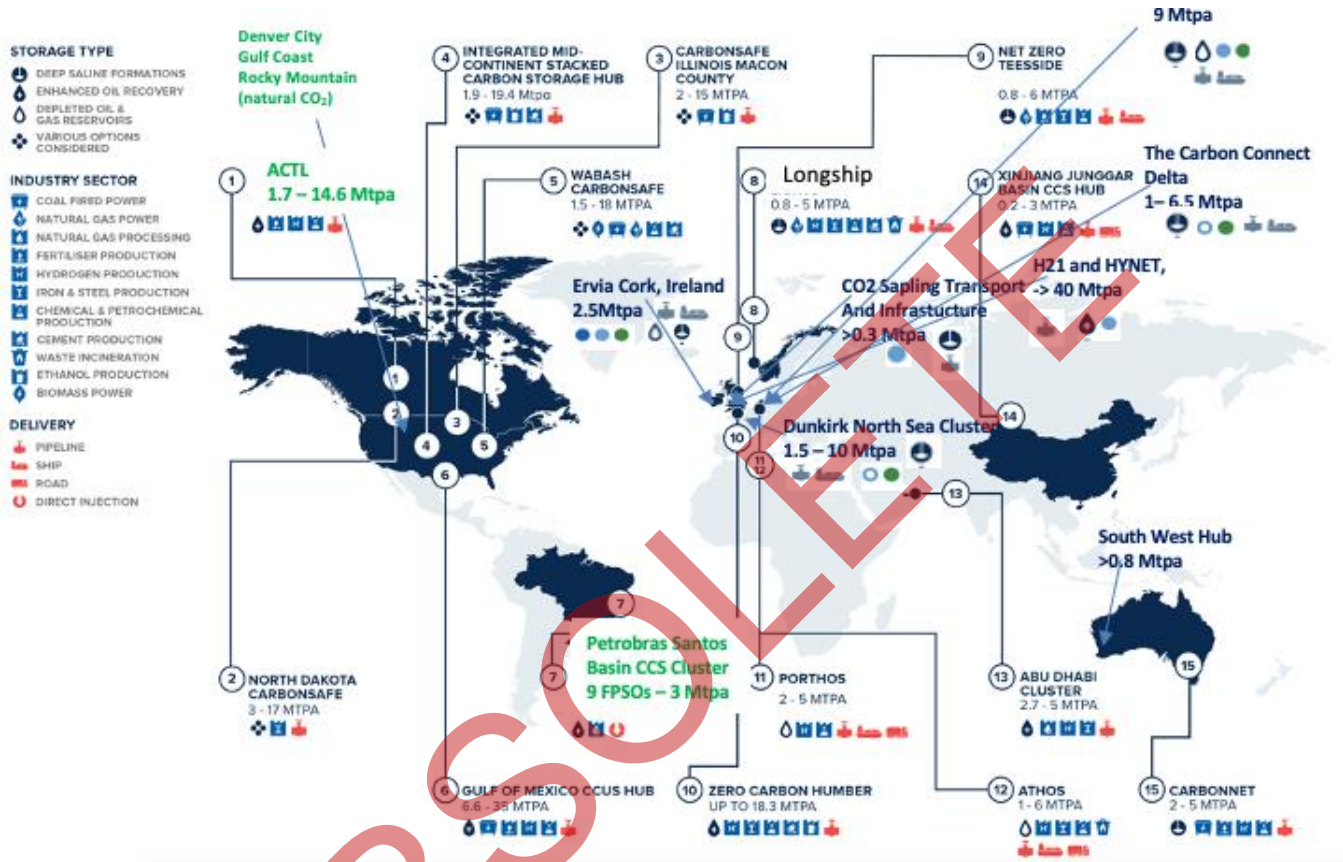
Development of hubs will require commercial models for cost and risk-sharing. IEAGHG (2018) studied four models:

- Public transport and storage company (T&S)
- T&S as regulated assets
- Anchor CCS project with 3rd party access
- CO₂–EOR

³⁸ <https://www.alignccus.eu/about-project>

IEAGHG concluded that private investments can occur only if four enablers are addressed simultaneously:

- The risk of carbon leakage (to other countries) is mitigated.
- The margin of certainty is provided through subsidies for industrial sectors.
- Business cases for capture and infrastructure are decoupled.
- There is public-private risk-sharing.



Notes:

Mtpa = Million tons per year

Two set of symbols have been used for industry sector: As above and

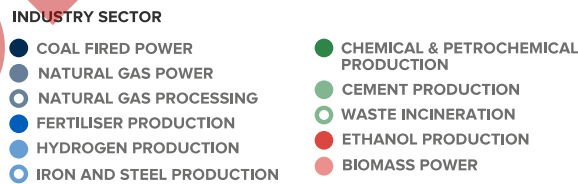


Figure 3.6. Hubs in operation (green) and planned as of November 2020. Numbered hubs from GCCSI (2020), courtesy of GCCSI. Additions by CSLF.



Figure 3.7. The Longship project. The photos show the location of the CO₂ sources, the ship transport, and the storage location. The other dotted lines indicate potential additional CO₂ sources. Courtesy of Gassnova.

Details of the three last points will have to be addressed case by case by the hubs in Figure 3.8. For example, in Longship, one consortium is responsible for transport and storage, whereas the industries are responsible for capture. The project is to be developed with strong support from the Norwegian government. In the Netherlands, the company Carbon Collectors offers transport of CO₂ on barges and subsequent storage.

In addition to the points mentioned above, there will be a need for real-time measurements at strategic locations to verify that the CO₂ stream compositions are according to specifications. There will also be a need for mass flow metering. Several technologies for metering will have to be tested and qualified, and a commonly accepted standard will be required.

3.2.3. Technology needs for CO₂ transport and infrastructure

The technologies to develop CO₂ hubs exist and are mature. However,

- Work to optimise pipeline transport should continue.
- Ship transport must be qualified, in particular systems for offshore loading.
- Internationally recognised standards for CO₂ transport must be developed.
- Proper commercial models for hubs must be identified.
- Local adaptations and optimisations will be needed.
- Experience and learnings from operation of hubs are still limited.

3.2.4. Conclusions and recommendations for CO₂ transport and infrastructure

The development of CO₂ hubs is progressing. One system, the ACTL in Canada, became operational in 2020, and another, Longship in Norway, passed the FID the same year. By the end of 2020, 20 other hubs were in advanced or early planning. Together, these have the potential to capture and store more than 240 Mt CO₂/year.

Recommended priority actions for CCUS hubs

Toward 2025:

- Start the construction of at least five new CCUS hubs.

Toward 2030:

- Ensure rapid build-out of strategic power and industrial CO₂ capture clusters, with common CO₂ transportation and storage infrastructure (hubs), to secure that CCUS hubs collect and store at least 400 Mt CO₂/year.

3.3. Storage

3.3.1. Status storage

Storage works, as proven by the 26 large-scale projects³⁹ that store CO₂ in geologic formations (IEA 2020b). Five have dedicated storage in saline formations, whereas the remaining inject CO₂ into hydrocarbon fields for EOR. In addition, there are some smaller test sites and a number of demonstration and pilot-scale projects.

National and international regulations and standards on CO₂ storage in geologic formations (EU 2009a,b,c; ISO 2017; US EPA Class VI regulation) have at least three prerequisites before injection can start to secure safe long-term (millennium) storage of CO₂:

- The identification of suitable storage sites and validation of their storage capacity.
- Characterisation of the storage sites, as required in the regulation.
- Storage management plans that include tools and methods to monitor that injected CO₂ behaves as predicted in the permits, without leaks, and that proper mitigation measures can be put in place in case of leaks or unexpected behaviour.

There has been progress in all three aspects between the 2017 TRM and 2021 TRM. Much of the progress is happening through international cooperation.

CO₂ is used for enhanced hydrocarbon recovery. Whereas enhanced coal bed methane production (ECBM), enhanced gas recovery (EGR), and enhanced gas hydrate recovery (EGHR) are applications still being developed or tested in pilot-scale tests, enhanced oil recovery (EOR) is widely used, mainly onshore in North America. In the United States, just under 30% of the CO₂ used for EOR comes from anthropogenic sources.⁴⁰ The rest is naturally occurring. In EOR operations, 90%–95% of the injected CO₂ stays in the ground (Eidan et al. 2015); thus CO₂ EOR is a way to safely store anthropogenic CO₂. ISO (2019) has developed an international standard for CO₂–EOR.

Issues that emerge when discussing CO₂–EOR in a climate mitigation context include:

- **The transition from CO₂–EOR to pure and dedicated CO₂ storage.** There are no specific technological barriers or challenges per se in transitioning and converting an onshore CO₂–EOR operation into a CO₂ storage operation. The main differences between the two types of

³⁹ Large scale projects: >0.8 Mt CO₂/year for power plants; >0.4 Mt CO₂/year for industry

⁴⁰ <https://www.iea.org/commentaries/can-co2-eor-really-provide-carbon-negative-oil>

operations stem from legal, regulatory, and economic differences, in particular monitoring and verification requirements (see Eidan et al. 2015). ISO has work in progress on this topic.

- **The large potential for CO₂-EOR in offshore basins that remains unexploited.** Again, there are no technological barriers for this, but economics, lack of CO₂ supply, and lack of regulations are important factors (CSLF 2017b; Eide et al. 2019b).
- **The question of the net impact on CO₂ reductions from CO₂-EOR when accounting for the CO₂ released during combustion of the additional oil.**

CO₂ storage capacity

Estimating CO₂ storage capacity is a challenge, especially where geological and geophysical data coverage are sparse. The methods to evaluate capacity vary, but the release of the Society of Petroleum Engineers' (SPE's) Geologic Storage Resources Management System (SRMS) (SPE 2017) was an important step towards a unified approach. A global application of SRMS is underway by Pale Blue Dot and the GCCSI, funded by the Oil and Gas Climate Initiative (OGCI)⁴¹.

So far, 12,000 Gt potential storage (undiscovered resources) capacity has been identified in the SRMS, of which 400 Gt are classified as discovered resources (GCCSI 2020a). The estimate falls within the range of 8,000–55,000 Gt CO₂, suggested by IEA (2020b), which will be sufficient for centuries. Russia, North America, and Africa are holding the largest capacities. Substantial capacity is also thought to exist in Australia (IEA 2020b).

Globally, the storage capacity in abandoned oil and gas fields is probably less than 1% of the total capacity (GCCSI 2020a). Mineralisation of CO₂ (storage in basalt or other similar formations) offers potential to the global storage inventory (see also Section 3.5.4).

Zahasky and Krevor (2020) found that even the most ambitious IPCC scenarios with respect to CO₂ storage will not require more than 2,700 Gt capacity by 2100 (a few scenarios have more than 40 Gt CO₂/year storage by 2100), significantly less than the above estimates.

Much effort has been spent by the technical CCS community in improving the estimation of storage resources. These studies have led to significantly improved global storage estimates (CSLF 2019b). However, storage efficiency, the proportion of pore space utilised, is very low. In the case of saline formations, CO₂ storage efficiency represents 1%–4% of the bulk volume (with 15%–85% confidence; CSLF 2019b). To examine options to improve the utilisation of the pore space resource, CSLF established a task force to examine existing technologies developed in the hydrocarbon industry, maturing pressure management technology, and innovative emerging technologies, as well as general principles for storage operations. Four evolving technologies were reviewed as potential methods for improving the utilisation of pore space associated with CO₂ storage (CSLF 2019b):

1. Pressure management
2. Microbubble CO₂ injection
3. CO₂ saturated water injection and geothermal energy
4. Swing injection

The report concluded that technologies represent strong value to the optimisation of site storage operations, yet many of them require further technical development before they could be deployed at scale commercially.

Characterising storage sites

Several projects have made contributions to better characterisation of CO₂ storage sites and the storage management plants. An example is GeoCquest, a research consortium of Melbourne, Stanford, and Cambridge universities, which has developed an advanced modelling workflow to quantify CO₂ flow and trapping by the different mechanisms over time and the influence of fine-scale heterogeneities (millimetre to metre scale) for improved prediction of CO₂ flow dynamics. Successful

⁴¹ <https://oilandgasclimateinitiative.com/launch-of-the-worlds-first-independent-catalogue-of-co2-storage-resource-for-ccus/>

application of approaches like this has the ability to reduce uncertainty during commercial project decision-making and help facilitate post-closure transfer.⁴²

Other examples are below:

- A portal by CO₂ DataShare Consortium⁴³, launched in February 2020, will enable researchers and engineers worldwide to improve understanding, reduce costs, and minimise uncertainty associated with CO₂ storage by testing models on real CO₂ storage data.
- The U.S. Department of Energy funded the National Energy Technology Laboratory (NETL) CarbonSAFE⁴⁴ initiative (and previous iterations), which has driven the deployment of several projects, and many more are in the pipeline. This was achieved through characterisation and appraisal drilling and interpretation.

Several infrastructure projects have characterised large-scale storage systems, sometimes improving the characterisation tools in the process. Examples are the Endurance site, offshore the United Kingdom (Teesside), and the Aurora site, offshore Norway. The latter has drilled an appraisal well, as has CarbonNet, Australia.

Characterisation of storage sites can be a lengthy process, from a few years to a decade. Several characterisation studies have been undertaken at regional and national levels. These studies have been conducted in the European Union, Norway, the United States, Australia, China, and South Africa. The resulting atlases will serve as starting points for site-specific studies.

Monitoring

Ajayi et al. (2018) gives an overview of monitoring technologies that have been deployed at the field-scale projects Sleipner (Norway), Kertzin (Germany), Weyburn (Canada), Otway (Australia), Cranfield (USA), In Salah (Algeria), and Rumaitha (United Arab Emirates). The overview did not include Quest (Canada) (IEAGHG 2019b) or Tomokomai (Japan CCS Company 2020).

Several funding agencies and mechanisms - including NETL, ACT, and Australian agencies - and industry have granted substantial funds for activities whose aims are to reduce costs for monitoring technologies. Monitoring technologies and tools that have advanced since 2017 include (e.g., NETL 2020):

- Fibre optics sensing
- 4D and real-time seismic monitoring
- Passive/micro-seismic monitoring (see also footnote 45)
- Pressure-based monitoring
- Distributed acoustic sensing (DAS)
- Models and simulation by combining monitoring and characterisation data with advanced computation

To this could be added use of tracers (for example, see Ju et al. 2020 and the University of Oslo⁴⁶).

The Australian Otway Stage 2C project⁴⁷ has provided important findings into stored CO₂ monitoring. The research assessed detection thresholds for CO₂ in a storage reservoir (as little as 5,000 tonnes). The demonstration provides CCS stakeholders with confidence that CO₂ migration predictions can be verified with existing monitoring technologies. The success with the Otway Stage 2C project has paved the way for development in fibre optics sensing and new seismic- and pressure-based cost-effective monitoring technologies.

⁴² Max Watson, CO2CRC, personal communication

⁴³ <https://co2datashare.org>

⁴⁴ <https://netl.doe.gov/coal/carbon-storage/storage-infrastructure/carbonsafe>

⁴⁵ <https://climit.no/project/demonstration-of-optimized-baseline-seismic-monitoring-network-for-the-horda-platform-region-h-net-project/>

⁴⁶ <https://www.mn.uio.no/geo/english/research/projects/ico2p/>

⁴⁷ <https://co2crc.com.au/co2research/stage-2c/>

Cost of CO₂ storage

The cost of CO₂ storage will be site-dependent. IEA (2020b) indicates that costs for storage in the United States will vary between \$5 and \$55/t CO₂ (2017 USD) for both onshore and offshore storage, with possible negative cost in the case of EOR. Approximately 60% of the onshore and only 6% of offshore sites have cost less than \$10/t CO₂ (USD). However, cost estimates for CO₂ storage in geologic formations are difficult to find and should be researched.

3.3.2. Technology needs CO₂ storage

As previously noted, CO₂ storage has been proven to work. Technology needs are mostly focused on optimizing storage processes to further reduce uncertainty and costs, and to facilitate the deployment of large-scale storage projects through improved site characterization and planning.

Characterisation

Although not strictly a technical issue, characterisation in terms of national and regional atlases with pre-commercial assessment of storage capacity should be commenced by government geological surveys (IEA 2020b).

Storage management plans

Proper storage management plans should include:

- Ensuring well integrity
- Understanding the pressure build-up during injection
- Understanding the caprock integrity
- Monitoring plans, including advanced sensing and real-time monitoring, topics already being addressed by international research projects
- Mitigation plans

Although many of the listed topics will be site-specific, RD&D will contribute to cost reductions.

Other RD&D topics include (see MI 2018 and ZEP 2017⁴⁸ for details):

- Modelling
 - Advancing multiphysics and multiscale fluid flow models to achieve gigatonne/year capacity
 - Models for improved understanding and prediction of fundamental reservoir and overburden processes
- Reservoir and overburden
 - Understanding dynamic pressure limits for Gt-scale CO₂ injection
 - Improving characterization of fault and fracture systems
 - Understanding long-term reservoir behaviour
 - Increasing knowledge of sealing capacity of caprocks
 - Understanding the effects of impurities in the CO₂ stream in the storage reservoir
- Wells
 - Optimizing injection of CO₂ by control of the near-well environment
 - Locating, evaluating, and remediating existing and abandoned wells
 - Establishing, demonstrating, and forecasting CO₂ well integrity
- Monitoring
 - Developing, demonstrating, cost-optimising, and commercialising monitoring technologies to demonstrate containment, enable storage site closure, assess anomalies, and provide assurance

⁴⁸ ZEP (2017a) gives an extensive review of CO₂ injection and storage technologies and needs.

- Achieving next-generation seismic risk forecasting
- Developing online/real-time monitoring systems (several monitoring technologies) over large areas, combined with machine learning
- Regulatory and public acceptance issues
 - CO₂ storage resource portfolios and exploration and appraisal procedures adapted to CO₂ storage to reduce uncertainties
 - Identification of where CO₂ storage conflicts with/has impacts on other uses and/or resource extraction and inclusion in resource management plans (for example, oil and gas production, marine and maritime industry, and production of drinkable water)
 - Storage closure, post-injection monitoring, and liability transfer
 - Experience with closure and post-closure procedures for CO₂ storage projects (must wait until there are injection projects that close down, as In Salah, Algeria, has done)
 - Procedures for securing and closure of CO₂ storage and post-closure monitoring
 - Procedures for transferring liability

Results from RD&D projects must be commercialised and implemented.

Finally, but not least, onshore CO₂ geological storage has sometimes met public opposition, particularly in Europe. Public outreach in the form of scientifically founded but popularly formulated information campaigns are needed to address concerns and needs for information.

3.3.3. Conclusions and recommendations for CO₂ storage

- CO₂ storage is proven and safe.
- Global storage capacity is sufficient to accommodate even the most ambitious IPCC scenarios.
- Progress has been made in modelling and monitoring tools and methods that are important for site characterization and storage management plans.
- RD&D regarding modelling and monitoring tools and methods must continue, along with commercialization and deployment in large-scale projects.

Recommendations for CO₂ storage

Toward 2025:

- Commercialise monitoring technologies under development.
- Continue characterising CO₂ storage sites.

Toward 2030

- Characterise sufficient storage sites to secure an increase by a factor of 10–15 from the 2020 level (40 Mt CO₂/year) of long-term isolation of CO₂ from the atmosphere.
- Reduce monitoring and verification costs by 20% from 2020 levels.

Toward 2050

- Characterise sufficient storage sites to secure an increase by a factor of at least 100 from the 2020 level of long-term isolation of CO₂ from the atmosphere.

What will it take to inject around 5,000 Mt CO₂ per year? Ringrose and Meckel (2019) found that the average injection rate, based on 60 years of injection data from 9 wells, was 0.53 Mt CO₂ per year and 0.7 Mt CO₂ per year for offshore wells. Thus, the target injection rate by 2050 will require more than 8,000–11,000 wells. According to Ringrose and Meckel (2019), this is manageable, considering the historic petroleum well deployment rate (see also IEAGHG 2017a).

3.4. Utilisation

3.4.1. Overview of utilisation options

CO₂ has been utilised in various applications and products for decades. There are several forms of CO₂ reuse, or CCU, already in use or being explored, including urea production, ethylene oxide production, ethanol production, utilization in greenhouses, conversion to polymers, methanol and formic acid production, production of bioplastics, and the cultivation of algae as a pathway to bioenergy animal feed, as well as other products. These will not lead to permanent storage but may contribute to reduced CO₂ emissions, for example, if the captured CO₂ replaces new, fresh hydrocarbons as source for carbon. Also, there may be other related benefits; for example, the utilization of waste CO₂ in greenhouses in the Netherlands already leads to a better business case for renewable heating and a rapid growth of geothermal energy use in the sector. These options could lead to a reduction in capture costs and transport optimization and learnings.

There are multiple pathways for conversion of CO₂ into a wide range of products (Figure 3.8). For the purposes of this section, the utilisation concepts discussed will focus on conversion pathways, as working fluid applications are either more applicable for power generation specifically (such as supercritical CO₂ power cycles and enhanced geothermal recovery) or hydrocarbon recovery (such as EOR).

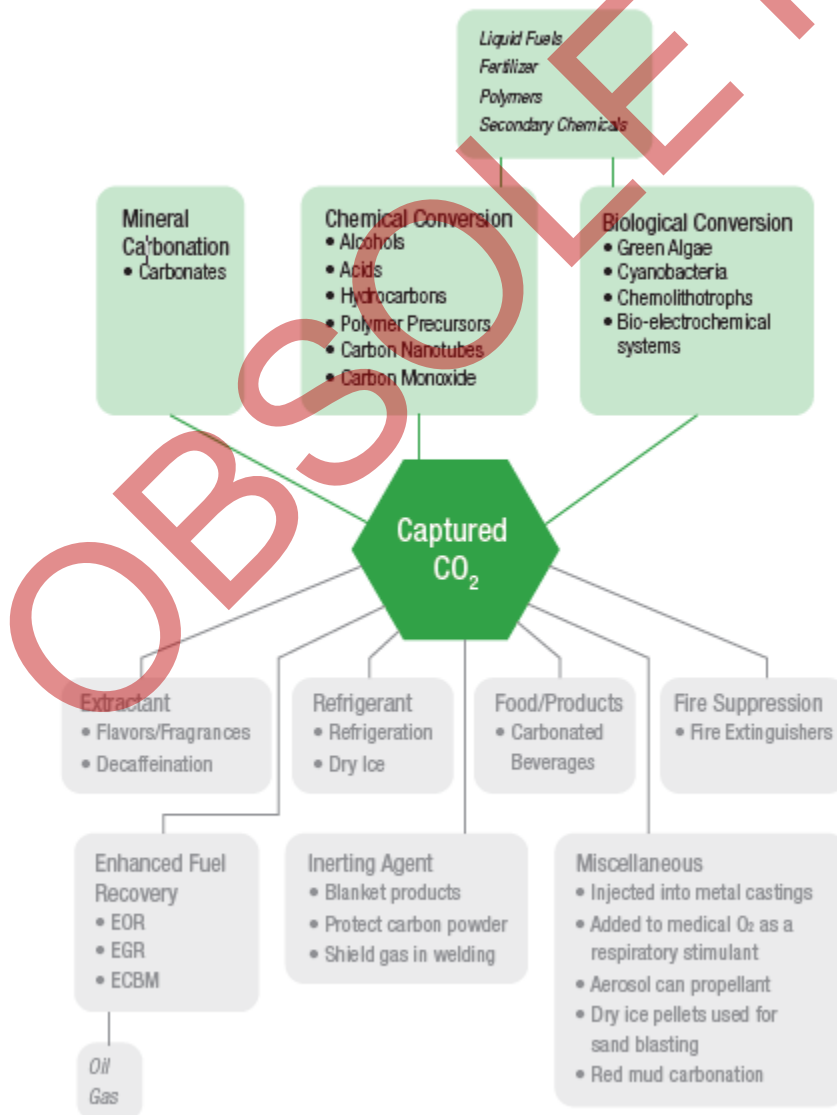


Figure 3.8. CO₂ utilisation pathways. Source: Gaseous Carbon Waste Streams Utilization: Status and Research Needs, National Academies of Sciences, Engineering, and Medicine (NASEM), 2019

More generally, the typical conversion pathways for CO₂ utilisation can be defined as mineralization, thermochemical, electrochemical/photochemical, and biological. In general, mineralization and some biological approaches are considered more technically mature than the thermochemical, electrochemical, and photochemical routes (National Petroleum Council [NPC] 2019; NASEM 2019a). However, some chemical conversion routes have been commercialized, such as the CSLF-recognized SABIC project at Jubail City, Kingdom of Saudi Arabia. This project converts 500,000 metric tons of CO₂ into products such as urea, methanol, and oxo-alcohols, as well as CO₂ for the food and beverage industry⁴⁹.

Studies show the potential markets for CO₂ utilisation can increase in the future if the technologies begin to mature and markets and business frameworks are established (Figure 3.9).

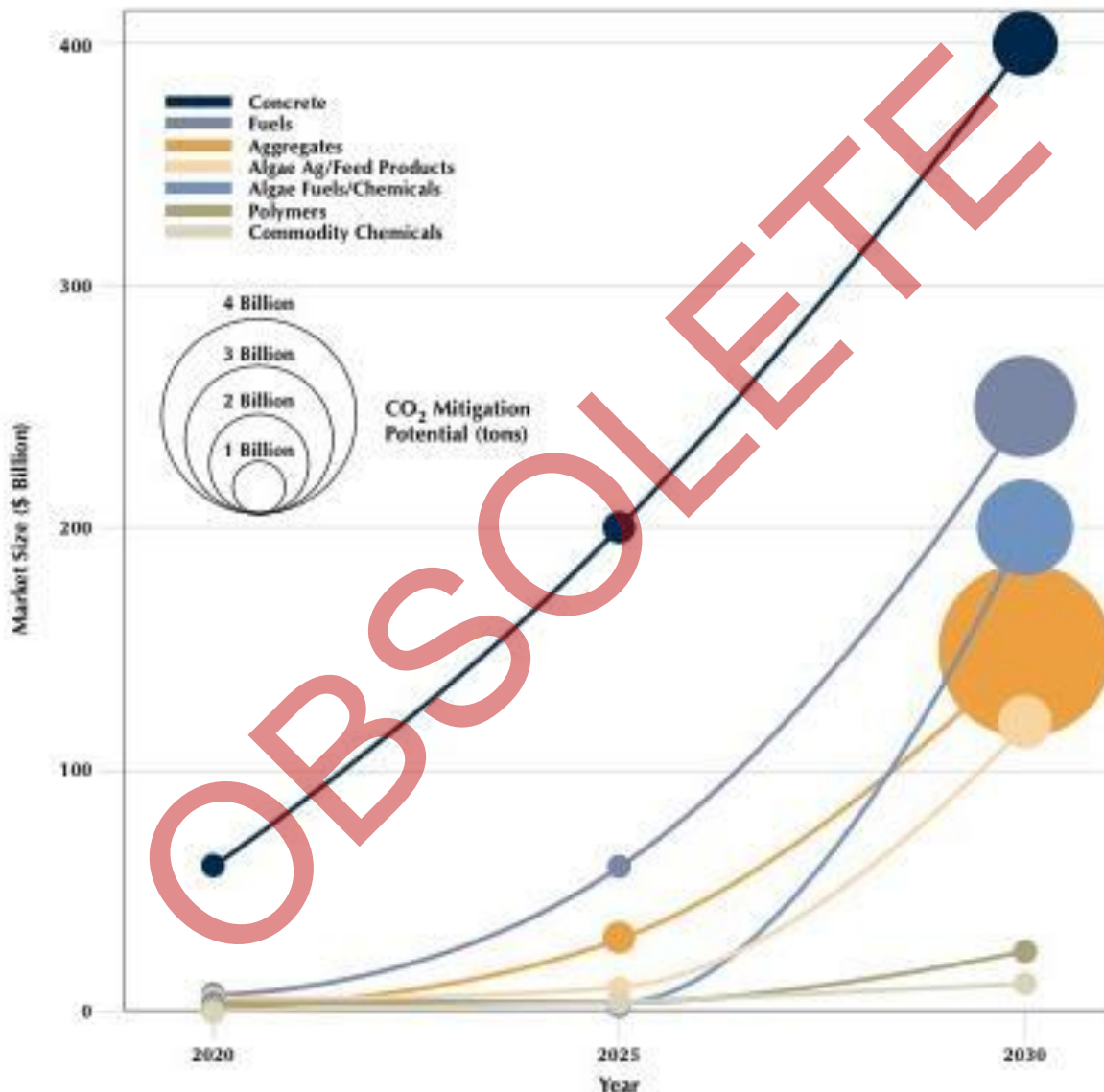


Figure 3.9. Market size and GHG mitigation potential for selected CCU sectors

Source: Carbon Utilization: A Vital and Effective Pathway for Decarbonization, Center for Climate and Energy Solutions, (C2ES); 2019

⁴⁹ Presentation at the CSLF Technical Group Meeting, virtual, September 2020, <https://www.cslforum.org/cslf/sites/default/files/documents/SaudiArabia2020/CO2-Capture-and-Utilization-at-SABIC.pdf>

When taken cumulatively, carbon utilization options have the potential to deliver meaningful improvements in environmentally sustainable products while providing significant revenue generation.

Conversion pathway descriptions

Thermochemical conversion uses catalysts and energy, typically heat, and other reactants, such as hydrogen (H₂), to convert CO₂ into hydrocarbon products. Urea is one common product, widely used today, that is thermochemically produced from CO₂ and ammonia (NH₃). However, CO₂ is a thermodynamically stable molecule, and thus presents challenges in its use as a chemical feedstock. The energy for the process and the other reactants used must come from low-carbon sources to ensure a net CO₂ reduction benefit on a lifecycle basis.

Electrochemical and photochemical conversion processes use electricity or sunlight to convert CO₂ and other reactants into products. In the electrochemical pathway, electricity is used to reduce CO₂ into simpler carbon molecules such as carbon monoxide (CO), which can then be combined with other reactants, such as H₂, to produce a wide range of products. The photochemical process uses CO₂, water, and sunlight to produce various fuels and chemicals, which are sometimes referred to as solar fuels.

Similar to the thermochemical route, a key factor is to ensure the availability of low-carbon sources of electricity and reactants so that an overall reduction in lifecycle CO₂ emissions is achieved.

Mineralization processes react CO₂ to form minerals, such as carbonates, which can be used in various building material applications. Mineralization processes typically require source materials such as calcium, magnesium, or silicate-bearing rocks that can react with CO₂ to form useful minerals. These source materials can come from natural rocks or from industrial wastes such as mine tailings. For example, mixing CO₂ with bauxite residue (red mud) has been demonstrated in Australia (GCCSI 2011). Mineralization approaches also can use CO₂ in the curing process of building materials. There are several companies that are currently commercializing these approaches (NPC 2019).

Biological approaches use photosynthetic or metabolic processes to convert CO₂ into products such as fuels, chemicals, animal feed, and various other products. These approaches use the inherent biology of organisms such as plants, bacteria, and algae for the conversion. There are a number of potential pathways and options, and there are numerous companies and organizations globally that are working on commercializing biological approaches to CO₂ conversion.

3.4.2. Technology needs CO₂ utilisation

The technology needs for CO₂ utilisation are dependent upon the CO₂ conversion approach and the pathway chosen. Additionally, even within some of these pathways, there are varying degrees of technological maturity. For example, the technology needs and level of maturity for an open pond algal system will be much different from those of a closed pond system. Since the first CSLF Task Force reports on CO₂ utilisation dating back to 2012 and 2013^{50,51}, there has been a significant increase in the body of work and knowledge in this area (Innovation for Cool Earth Forum; MI 2018; NASEM 2019; NPC 2019), which focuses on the technology and policy needs for moving carbon utilization technologies forward. These are summarized below.

Thermochemical conversion

For thermochemical conversion routes, catalysts and reactor system designs are critical to the efficient conversion of CO₂ into valuable products. Research can improve existing catalysts and reactor systems and discover new catalysts. Additionally, leveraging capabilities such as high-

⁵⁰ Phase 1 Final Report by the CSLF Task Force on CO₂ Utilization Options, Carbon Sequestration Leadership Forum, October 2012.

⁵¹ Phase 2 Final Report by the CSLF Task Force on CO₂ Utilization Options, Carbon Sequestration Leadership Forum, October 2013.

performance computing, artificial intelligence, and advanced manufacturing techniques can help identify, characterize, and functionalize novel catalysts into commercially viable systems.

While attention to catalyst development should focus on typical metrics such as activity, selectivity, and durability, it is also important to consider the final products. For example, products that are produced at low equilibrium could benefit from efficient removal during production, integration of catalyst and reactor design, and coupling reactions.

Fundamental work is required at the laboratory and bench scale, coupled with advanced modelling and simulation tools. Additionally, as technologies are developed, pilot-scale testing can help prove out the concept and address integration issues prior to commercial deployment.

Electrochemical and photochemical conversion

Electrochemical and photochemical conversion systems share some common challenges with thermochemical systems. For example, catalysts and reactor systems are also important for these systems, as is product separation and removal. In addition, membranes, electrolyte materials, and novel cell stack design and manufacture ensure robustness and efficient utilization of electricity or sunlight in the process. Electrolytes that have high solubility of CO₂ can help improve performance and overall efficiency.

Fundamental R&D, along with eventual pilot-scale testing of advanced technologies, is needed. Integrated system designs and the leveraging of advanced computational tools and manufacturing techniques can develop transformative systems.

Mineralization processes

Mineralization processes are some of the more advanced pathways available today for conversion of CO₂ and have some of the most near-term opportunities for commercialization. Key R&D needs for continued development of these processes include:

- Understanding of rates of reaction, selectivity, and crystal growth, which can help in the control of carbonation reactions and, ultimately, final products
- Customization of end-product properties that result in greater storage of CO₂
- Advanced modelling and analytical tools and capabilities that improve understanding of structure–property relationships of mineralization products
- Process designs that can increase conversion rates, optimize final products, and improve energy efficiency
- Testing and validation of products at relevant scales to ensure performance specifications are met

Biological conversion

Biological approaches for conversion of CO₂ range from lab-scale to commercial-scale technologies. Similar to the thermo-, electro-, and photochemical conversion routes, biological approaches would benefit from faster kinetics, improved selectivity, and more durable or contaminant-resistant materials. R&D efforts should focus on identification of natural organisms and synthetic biological approaches to improve these properties. Coupling design of the biological material with the reactor, product separation, and removal system can lead to improved efficiencies. Dewatering, harvesting, and culture monitoring can help advance biological approaches. Computational techniques and advancements in bio-engineering approaches can help improve metabolic rates and development of targeted products.

For later-stage R&D, conducting pilot-scale testing to integrate components and validate performance is critical.

Crosscutting needs

Lifecycle assessments (LCAs)

LCAs for all utilization approaches are necessary. The challenge with LCAs for utilization is that the approaches and pathways vary greatly and, in some cases, are still evolving. However, conducting LCAs can help guide R&D towards approaches that have the greatest energy and environmental benefit. Developing appropriate, transparent benchmarks and ensuring consistency will ensure that these approaches are having the desired outcome: reducing overall CO₂ emissions.

Technoeconomic assessments (TEAs)

TEAs are necessary to understand the economic and environmental potential of CO₂ utilization options. Standardized and transparent assumptions can help formulate consistent TEAs. While many CO₂ utilization options are continuing to develop and emerge, conducting TEAs throughout the development cycle can help monitor progress and performance.

Product certification

Many utilization technologies are developing products that will need to undergo rigorous testing to ensure they meet technical specifications. For example, many mineralization products will have potential use in various building and construction materials, which have set standards or specifications. CO₂ utilization products will need to meet these standards, but consideration should also be given to the potential unique properties and advantages some of these materials may possess when considering their ultimate end use.

3.4.3. Recommendations for CO₂ utilisation

Toward 2025:

- Governments should continue to make investments in public–private partnerships or projects that continue to develop and mature promising utilization technologies (technology push).
 - Specifically, for more advanced technologies, governments should invest in pilot-scale or demonstration projects, particularly those that integrate capture and utilization.
 - For earlier-stage CO₂ utilization options, governments should continue to make investments in R&D that addresses key issues surrounding chemistry, biology, materials science, and engineering for these concepts, while also incorporating enabling technologies such as artificial intelligence, advanced manufacturing, nano-scale developments, automation, and robotics.
- Governments should encourage industry, regulators, and academia to develop consistent and transparent methods for LCAs and TEAs.
- The International Test Center Network (ITCN) should encourage its member test facilities to incorporate carbon utilization pilot-scale testing, as allowable, within their test portfolios. Governments should establish frameworks that promote a business case for CO₂ utilizations. This includes regulatory frameworks as well as incentives (for example, the 45Q tax credit and low-carbon fuel standard in the United States) that promote market uptake (i.e., market pull).
- Policies should be promoted that foster uptake of “green” products or products that utilize CO₂ in their manufacture.

Toward 2030:

- Governments should continue the development and deployment of second-generation utilization technologies by investing in pilot-scale and demonstration projects.
- Governments should establish a goal that a certain percentage of all government-procured products meet a low-carbon or “green” standard.

3.5. Negative emissions technologies (NETs)

3.5.1. Brief overview of NETs

- Negative emissions technologies (NETs) are expected to play an important role in achieving deep decarbonisation targets. NETs are a suite of technologies that remove carbon from the atmosphere and store it. In its 2019 report, *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, the National Academy of Sciences (NASEM) evaluated six areas of NETs (2019b):
 - **Coastal blue carbon:** The deployment of methods that increase the amount of carbon stored in plants and soils of tidal marshes, wetlands, and seagrass beds
 - **Terrestrial carbon removal and storage:** Agricultural and forestry management and practices that increase or enhance the amount of carbon stored in soils
 - **Bioenergy with carbon capture and storage (BECCS):** The use of biomass, which absorbs CO₂ to grow, and its subsequent conversion into products such as electricity, fuels, and chemicals, coupled with carbon capture and permanent storage of CO₂
 - **Direct air capture (DAC):** The removal of CO₂ from the atmosphere through chemical and engineered techniques
 - **Carbon mineralization of CO₂:** The use of reactive minerals to form chemical bonds with CO₂, resulting in its capture and storage
 - **Storage of supercritical CO₂ in deep sedimentary geologic formations:** The injection and storage of CO₂ in a geologic formation such as a saline aquifer. While technically not a NET, it is an option for the sequestration component of BECCS or DAC.

The NASEM (2019b) report also provided a summary (Table 3.2) of the cost and impact potential of NETs based on current technology and understanding.

Table 3.2. Cost, limiting factors, and impact potential of NETs with current technology and understanding

Negative Emissions Technology	Estimated Cost (\$/t CO ₂) L = 0–20 M = 20–100 H = >100	Global Safe Potential Rate of CO ₂ Removal Possible Given Current Technology and Understanding and at <\$100/t CO ₂ , Gt CO ₂ /year ^a
Coastal blue carbon	L	0.13
Terrestrial (afforestation/reforestation)	L	1
Terrestrial (forest management)	L	1.5
Terrestrial (agricultural soils)	L to M	3
BECCS	M	3.5–5.2
DAC	H ^b	0
Mineralization	M to H	Unknown

Notes: “Safe” rate of CO₂ removal means that the deployment would not cause large potential adverse societal, economic, and environmental impacts. Estimated rates assume full adoption of agricultural soil conservation practices, forestry management practices, and waste biomass capture.

The number of significant digits reflects the state of knowledge among different NETs.

^a Global removal rate based on coastal wetland area lost since approximately 1980 and annual burial rate with restoration; does not include active management of existing areas or managed wetland transgression.

^b Cost for deployed air capture remains substantially above \$100/t CO₂ (as high as \$600/t CO₂).

Source: NASEM 2019b

For the purposes of this roadmap, which is focused on CCUS, this section will cover BECCS, DAC, and carbon mineralization. Further, mineralization in this context will primarily be focused on reactive minerals and storage, not mineralization as a carbon utilization approach. Also, storage of supercritical CO₂ is covered in the “Carbon Storage” section of this roadmap.

3.5.2. Bioenergy with carbon capture and storage (BECCS)

BECCS is a concept in which biomass, which absorbs CO₂ through photosynthesis, is converted into a product and the CO₂ that results from that process is subsequently stored in a geologic formation. Biomass is widely used today throughout the world to produce power, fuels, and chemicals. Biomass can be converted into these products through various methods such as 1) combustion for heat and power, 2) thermochemical conversion to fuels and chemicals, and 3) fermentation processes to fuels and chemicals. These processes are widely established and well known today. As such, costs are relatively understood, along with supply chains and logistics. A key consideration for biomass options is understanding the LCA of carbon throughout the process, particularly the land, agriculture, and forestry practices used to grow and harvest the biomass.

The key component is the application of CCS to biomass conversion processes. Fortunately, many of the challenges associated with carbon capture for large point sources are shared by bioenergy processes, and technologies developed for other applications, such as fossil-fuel-fired power generation and industrial sources, will also have applicability to biomass, with some expected modification to account for differences in gas mixture and operation conditions. In some cases, CCS applications for biomass can be much simpler, such as fermentation processes, in which a highly pure stream of CO₂ is already produced and requires only dehydration and compression to produce a storage-ready stream of CO₂.

Today, BECCS is not widely deployed, but active pilot and demonstration projects are underway. For example, the U.S. Department of Energy has funded a demonstration project in collaboration with Archer Daniels Midland. This project is capturing nearly one million metric tons per year from an ethanol production facility in Decatur, Illinois, and storing it in a saline formation.⁵² Additionally, the Drax Biomass Power Station in North Yorkshire, UK, is conducting pilot-scale carbon capture tests. Drax had previously converted several coal-fired units to operate on biomass. In 2019, the company conducted its first pilot-scale carbon capture test, and in autumn of 2020, it installed a second carbon capture test facility.⁵³

3.5.3. Direct air capture (DAC)

Direct air capture (DAC) is the removal of CO₂ from the atmosphere via chemical and mechanical means. It typically employs a liquid solvent or a solid sorbent. CO₂ is already removed from the atmosphere today, but primarily as a by-product of oxygen and nitrogen production. CO₂ is often used locally for various applications. DAC differs from these processes in that it is seeking to remove large quantities of CO₂ by specifically targeting its capture.

DAC is generally considered to be a flexible technology, meaning it can be located anywhere. However, site-specific conditions such as land, water, and energy availability; end-use market or disposition of the CO₂, i.e., storage; and general infrastructure capacity will factor into overall siting and the subsequent economics.

DAC is thought of mostly as an early-stage technology. and while high costs remain a challenge, there are several companies developing commercial projects. Similar to deployment of CCUS for large point sources, market conditions and policy, legal, and regulatory frameworks must exist to facilitate DAC deployment.

⁵² DOE NETL Archer Daniels Midland project factsheet: <https://www.netl.doe.gov/sites/default/files/netl-file/FE0001547-Factsheet.pdf>

⁵³ DRAX website: <https://www.drax.com/about-us/our-projects/bioenergy-carbon-capture-use-and-storage-beccs/>

3.5.4. Mineralisation

Carbon mineralization is the approach of removing CO₂ from the atmosphere by using reactive minerals, typically rocks that contain calcium or magnesium. The approaches used can be either in situ (in the subsurface in geologic formations), ex situ (i.e., at the surface), or surficial (also at the surface; a distinction from ex situ is defined below).

In situ approaches are generally very similar to carbon storage approaches in which CO₂ is injected into a geologic formation. However, the CO₂ reacts more readily with the calcium- and magnesium-rich rocks (for example, basalts) and forms a solid. While this ensures permanent storage, it also can block pore space and make it more difficult for CO₂ to access other parts of the formation. Thus, characterization and proper siting of injection wells is important. There have been several pilot and demonstration tests of in situ mineralization, such as the CarbFix project⁵⁴ in Iceland and the Big Sky Regional Carbon Sequestration Partnership Phase II project⁵⁵ in Wallula, Washington, USA.

Ex situ mineralization occurs at the surface and is defined as the transport of solid reactants to the CO₂ capture site where it is reacted. These solid reactants must be crushed, ground, and designed for a specific particle size that can be optimized for a system. This requires energy, which subsequently impacts the economics but also the lifecycle carbon emissions. Challenges for ex situ mineralization are understanding the specific kinetics of mineralization and designing appropriate systems that can be cost-effective.

Surficial mineralization is defined as the reaction of CO₂-containing gas and fluids with alkaline industrial waste, mine tailings, or rocks/minerals that are exposed and have high surface area. One potential co-product benefit of surficial mineralization involving industrial wastes and mine tailings is the potential to extract minerals from these rocks. However, the kinetics, costs, energy, and lifecycle emissions for these processes must be studied.

3.5.5. Technology needs NETs

The technology needs for NETs vary based on the options that are applied. For example, the capture and storage technology needs for BECCS are identical to those for other large point sources: reducing the cost of capture and ensuring viable storage options. The one key difference is that bioenergy faces different technical challenges related to its conversion into products and logistics of transporting the biomass from field to conversion facility. A key component for BECCS is to understand the LCA around the biomass material itself.

For DAC, the technology needs are, in many ways, similar to carbon capture technologies for large point sources—the emphasis is on cost reduction and optimizing performance. The challenge, however, is that the process conditions for DAC are very different, particularly with the dilute stream that must be treated. For example, a coal-fired power plant flue gas has a CO₂ concentration in the range of 12%–15%, while CO₂ in the atmosphere is 0.04%. This presents a number of technical challenges such as moving large volumes of air, enabling efficient mass transfer contact of CO₂ with the capture material, and minimizing energy requirements for CO₂ capture and separation.

Mineralization concepts, similar to utilization, require a more in-depth understanding of the kinetics and, for in situ mineralization, an understanding of the rock mechanics. General characterization and mapping of the resource potential, both subsurface geology and mineral and industrial wastes at the surface, are necessary. It is also necessary to conduct studies to understand the overall environmental impact on land and water systems for mineralization concepts such as enhanced weathering or mined/extracted materials.

⁵⁴ CarbFix: <https://www.carbfix.com/>

⁵⁵ Big Sky Regional Carbon Sequestration Partnership Phase II basalt injection: <https://www.bigskyco2.org/research/geologic/basaltproject>

There are several general technical challenges that apply broadly to all NETs. For example, the potential land and water requirements for each NET should be evaluated to understand how this could limit or impact deployment. Energy requirements are important to the overall economics and LCA; in cases such as DAC and mineralization, the source, reliability, and accessibility of that energy are also important. Monitoring and verification methods are needed that can quantify and account for the CO₂. Early-stage R&D is necessary to develop better materials; understand kinetics; characterize and map sources and resources (biomass, land, water, energy, minerals) for supply/value chain optimization; and study environmental impacts/benefits. In addition, pilot-scale and demonstration tests are needed to validate first-generation concepts, provide better assessment of costs, identify potential business models, and understand legal and regulatory frameworks.

3.5.6. Recommendations for NETs

Toward 2025:

- Governments should take several actions in the science and technology of NETs:
 - Assess the NETs' potential in their countries, and identify key technical barriers and constraints (land, water, low-carbon energy, end-use disposition of the CO₂ in some cases [i.e., utilization or long storage], etc.).
 - Invest in "first mover" NETs pilot and demonstration projects.
 - Invest in R&D of transformational NETs.
- Industry, regulators, and academia should collaborate on developing the appropriate LCAs, TEAs, and quantification methodologies for various NETs to accurately quantify reductions and validate technologies.
- Governments should develop the appropriate legal and regulatory frameworks and business models (tax incentives, green procurement, etc.) that can facilitate deployment of a wide range of NETs, taking into consideration a variety of factors such as land, water, energy, and resource constraints.
- Where applicable, capabilities at existing test centres throughout the world, such as the International Test Center Network (ITCN), should be leveraged for DAC systems. The R&D community, utilizing existing collaborative mechanisms such as the CSLF, CEM, ACT, and others, should establish similar networks for other NETs such as carbon mineralization.

Toward 2030:

- Governments should continue to invest in transformational R&D and advance the most promising technologies to pilot scale and demonstration testing.

4. Policies and Incentives to Accelerate the Pace of CCUS Deployment

Since the 2017 roadmap, it has become clearer that the deployment of CCUS requires various non-technical measures and policies. A combination of strong policies, clear government commitment, and significant investment by industry and the finance sector can help drive deployment. Some private sector companies are beginning to include net-zero targets for their project portfolios, and it is clear that these efforts can further drive commercial implementation of CCUS. The CSLF and the CEM CCUS Initiative can both be helpful in this context to accelerate knowledge-sharing and ultimately deployment.

As a general proposition, a number of key non-technical measures will have to be considered and implemented according to the specificities of all relevant jurisdictions. These measures include *inter alia*:

- Implementing policies to mitigate the impacts of climate change, and ideally defining the role that CCUS can hold in a portfolio of responses.
- Developing national or regional CCUS strategies and implementation plans.
- Developing incentive frameworks, business models, and risk-sharing mechanisms that will enable CCUS projects' financeability.
- Implementing legal and regulatory frameworks to ensure safety and environmental integrity of CO₂ storage, transport, and capture operations, as well as for biomass supply chains in the case of BECCS.
- Implementing frameworks to enable cross-border transport of CO₂ for storage purposes.
- Communicating the importance of CCUS.

In general, the years since the 2017 CSLF TRM have seen a significant increase in attention brought to CCUS as one part of the portfolio of mitigation options and, consequently, also significant positive movement in implementing the needed frameworks.

As regards **climate policies**, a major shift has occurred over the past two years in countries' climate ambitions. The basis for this shift is the 2015 Paris Agreement, providing a universal and legally binding, global framework to drive down CO₂ emissions by setting both short- and long-term ambition levels and strong national commitments via nationally determined contributions (NDCs).

Since the 2017 TRM and in accordance with the Paris Agreement, several countries and regions have set economy-wide targets to achieve a balance between lowering emissions through sources and removing emissions through sinks, or so-called "net-zero emissions" or "carbon neutrality", by mid-century (target years ranging from as early as 2035 to 2060) (see Table 4.1). According to the United Nations⁵⁶, as of early 2021, these targets cover 110 countries jointly responsible for 65% of global CO₂ GHG emissions. While such targets are nationally determined and not directly comparable, they all contain the elements of both deep reductions of emissions via various technologies, coupled with various types of offsets and potentially CO₂ removal. These targets are likely to act as important high-level drivers for CCUS technology uptake.

⁵⁶ <https://news.un.org/en/story/2020/12/1078612>

Table 4.1. Notable national and regional net-zero targets (as of March 2021)

Country /region	Net-zero target year	Notes ⁵⁷
European Union	2050	Proposed legislation
Japan	2050	Proposed legislation
China	2060	In policy document
South Korea	2050	Proposed legislation
Canada	2050	Proposed legislation
United Kingdom	2050	In law
France	2050	In law

In some cases, net-zero ambitions are coupled with policies to abandon the use of fossil fuels altogether and/or policies to reduce subsidies for fossil fuels (more on this topic is available in IEA 2021).

More specifically, countries are expected to submit new or updated targets in their NDCs. By April 06, 2021, only 11 of the 190 Parties to the Paris Agreement, including the European Union, had submitted stronger targets⁵⁸. Although several large emitters had not submitted more ambitious NDCs, the positive sign is that, in connection with the Climate Ambition Summit⁵⁹, a growing number of countries have announced more detailed emission goals than those shown in Table 4.1, including the following:

- The European Union will cut CO₂ emissions by 55% in 2030, relative to 1990, and be climate-neutral by 2050.
- The United Kingdom will cut CO₂ emissions by 68% by 2030, compared to 1990, and be climate-neutral by 2050.
- China will become climate-neutral by 2060, with the intention to reach the emission peak before 2030.
- The United States of America will achieve net-zero emissions, economy-wide, by 2050.⁶⁰

However, the ambitions are insufficient to reach the goal of the Paris Agreement. The United Nations Environmental Programme (UNEP 2020a) estimated that, by 2030, the emission gap will be 12–19 Gt CO₂e/year for the 2°C target and 29–36 Gt CO₂e/year for the 1.5°C target if the unconditional NDCs are fulfilled.

This finding is further strengthened by a preliminary analysis by the United Nations Framework Convention on Climate Change (UNFCCC 2021) of 48 updated NDCs, representing 75 parties (the 27 members of the EU submitted one common NDC) were included. The NDCs represent 40% of the Parties to the Paris Agreement and almost 30% of the global GHG emissions. The analysis found that with the 48 new NDCs, GHG emissions by 2030 will be 0.5% lower than in 2010, whereas they would need to decline by 25% below 2010 levels and go net-zero by 2070 to reach the 2°C target and decline by 45% and reach net-zero by 2050 for the 1.5°C target. Thus, the UNFCCC (2021) concludes that the estimated reductions resulting from the updated NDCs (as of February 2021) fall far short of what is required, demonstrating the need for Parties to further strengthen their mitigation commitments under the Paris Agreement. A full report from the UNFCCC based on NDCs from all

⁵⁷ Source: <https://eciu.net/netzerotracker> and https://www3.nhk.or.jp/nhkworld/en/news/20210302_16/

⁵⁸ For continuous updates, see e.g. <https://climateactiontracker.org/climate-target-update-tracker/>

⁵⁹ <https://www.climateambitions Summit2020.org>

⁶⁰ <https://www.whitehouse.gov/briefing-room/presidential-actions/2021/01/27/executive-order-on-tackling-the-climate-crisis-at-home-and-abroad/>

Parties to the Paris Agreement will be published for the 26th Conference of the Parties, which will take place in November 2021.

Supplementing and reflecting the wider climate targets and strategies, it is expected that specific national CCUS strategies and policies for large-scale deployment will be the main drivers of CCUS deployment in the short to medium term. As the selected examples below illustrate, the specific CCUS policies provide incentives for capital investment, increased operating expenditure, or both.

In the **United States**, the 2018 45Q tax credit mechanism is being implemented. This mechanism offers carbon capture projects operational support via tax credits worth up to \$35 (USD) or \$50 (USD) per tonne of CO₂, depending on whether the CO₂ is injected for EOR or for permanent geological storage. This federal measure may also be coupled with state-level policies, such as the California Low-Carbon Fuel Standard, to offer significant financial support for carbon capture projects. In addition to the operational support for large-scale projects, the U.S. Department of Energy continues to support a sizeable R&D portfolio⁶¹.

In the **United Kingdom**, a CCUS strategy was established by the government in 2020, targeting a 10 MtCO₂ capture and storage capacity, to be in place by 2030 in up to four industrial hubs, or “SuperPlaces”. This is to be achieved via a CCS Infrastructure Fund (CIF) of GBP one billion (10⁹), coupled with other revenue mechanisms, details of which will be discussed in 2021.

The **Netherlands** is developing CCUS as part of the 2019 National Climate Agreement, with emphasis on clusters along the North Sea coast. The government will support the development of projects foremostly for industrial applications via the “SDE++” subsidy scheme, for a maximum period of 15 years, covering both operational and capital expenditure. The basis for calculating the subsidy is the EU Emissions Trading System (ETS) price, and subsidy amounts are adjusted yearly. In addition to SDE++, public authorities also play a strong role in developing common carrier infrastructure in key emission hubs, such as the Port of Rotterdam.

In **Norway**, the government and the parliament in December 2020 gave the go-ahead to provide significant public funding for the “Longship” CCS project, including the Northern Lights transport and storage project, the capture facility at a cement factory, and the option to part-fund carbon capture at a waste-to-energy facility. The Norwegian model is based on strong public investment, notionally covering roughly two-thirds of a total cost of NOK 25 billion (10⁹), which includes both the investment cost and ten years of operation.

Since the 2017 CSLF TRM, there has also been significant development in the **international legal framework** enabling cross-border transport of CO₂ for permanent storage purposes. In October 2019, the Parties to the London Protocol approved a resolution, brought forward by the governments of Norway and the Netherlands, for provisional application of the 2009 CCS Export Amendment. This allows Parties to provisionally apply the amendment and bilaterally agree to export and receive CO₂ for offshore geological storage, removing the last significant international legal barrier to CCS (IEAGHG 2020).

Progress has also been made in **international standards** for carbon capture, transport, and storage operations. The ISO has been developing standards for CCS since 2012. To date, ISO Technical Committee (TC) 265 has completed and published five standards and five associated technical reports. The standards help industry, governments, and regulators assess and ensure safety and quality of CCS technologies.

⁶¹ This includes efforts to reduce the cost of carbon capture while enabling high capture rates (>95%), optimizing storage operations, and developing viable utilization alternatives. This approach is looking at power, hard-to-abate industrial sectors such as cement and steel, and new efforts that are promoting low-carbon hydrogen production. It also includes an expanding portfolio on net NETs such as DAC, BECCS, and mineralization, which will play an important role in achieving decarbonization goals.

Finally, the recent trend to develop rules and norms, both voluntary and binding, for the **financial sector** to direct finance flows to sustainable investment deserves to be mentioned, as the financial sector is a key driver of sustainability and can have an impact on CCUS investment.

In parallel to various voluntary processes by the financial sector itself, the European Union is in a process of formulating the criteria for a “taxonomy” to define what can be considered sustainable investment. The EU Taxonomy on Sustainable Financing is the first regional framework, implemented via a binding EU Regulation (2020/852 of 18 June 2020), on “the establishment of a framework to facilitate sustainable investment”. The framework defines whether an economic activity qualifies as environmentally sustainable for the purposes of establishing the degree to which investment in it is environmentally sustainable. CCS employed in various economic activities is classified as “sustainable” if the criteria are met; however, coal-fired power with CCS is not eligible. The total impact on CCUS of the EU taxonomy is hard to assess, as no practical application yet exists.

Conclusions

- While several countries and regions have put forward net-zero targets by mid-century, analysis of the associated national policy plans shows that the world is not on track to meet the Paris Agreement target.
- Several countries have published strategies to deploy CCUS and have started implementing specific policies to incentivise large-scale projects.
- In addition, legal frameworks, international standards, and rules for sustainable investment can have a positive impact on CCUS deployment.

By the end of 2020, NDCs under the Paris Agreement fell far short of reaching the targets of the Paris Agreement.

- NDCs under the Paris Agreement must be strengthened.
- Strong efforts in post-COVID-19 recovery plans are needed to sufficiently decarbonize the economy.
- There is some reason for optimism, as many countries have reported various national strategies and specific CCUS policy initiatives for large-scale deployment that will be the main drivers of CCUS deployment in the short to medium term.

5. Follow-up Plans

The CSLF should continue to be a platform for an international coordinated effort to commercialize CCS technology, working with the CEM CCUS Initiative and, among others, the IEA, the GCCSI, and the IEAGHG.

The CSLF should continue to monitor progress in light of the identified priority actions, report the findings at ministerial meetings, and suggest adjustments and updates of the TRM. It is recommended that the CSLF, through its Chair and Executive Committee, monitor progress in CCUS made in relation to the recommended priority actions. Through the CSLF Secretariat, the Chair will:

- Solicit input with respect to progress of CCS from all members of the CSLF.
 - The Projects Interaction and Review Team should monitor the information exchange from large-scale projects.
 - Task forces should contribute when relevant (e.g., the Academic Task Force can follow developments in RD&D).
- Gather information from a wide range of sources, including collaboration partners, on the global progress of CCS.
- Prepare a simple reporting template that highlights the progress made in relation to the priority action.
- Report annually to the CSLF Technical Group and CEM CCUS.
- Report annually, or as required, to the CSLF and CEM CCUS ministerial meetings.

OBSOLETE

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Annex A. Abbreviations and Acronyms

\$	United States of America dollars
2DS	2°C Scenario
3-D	three dimensional
ACT	Accelerating CCS Technology
ACTL	Alberta Carbon Trunk Line
AR	augmented reality
AR5	Fifth Assessment Report
ATR	autothermal reformer
BD3	Boundary Dam Unit 3
BECCS	bioenergy with carbon capture and storage
C2ES	Center for Climate and Energy Solutions
CDR	carbon dioxide removal
CEM	Clean Energy Ministerial
CSLF	Carbon Sequestration Leadership Forum
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CCUS	carbon capture, utilisation, and storage
CO	carbon monoxide
CO ₂	carbon dioxide
CO ₂ e	carbon dioxide equivalents
CO ₂ -EOR	carbon dioxide-enhanced oil recovery
CRI	commercial readiness level index
CTSCo	Carbon Transport and Storage Company (Australia)
DAC	direct air capture
DAS	distributed acoustic sensing
DOE	U.S. Department of Energy
EC	European Commission
ECBM	enhanced coal bed methane production
ECCSEL	European Carbon Dioxide Capture and Storage Laboratories
EGR	enhanced gas recovery
EII	energy-intensive industries
EOR	enhanced oil recovery
ETC	Energy Transitions Commission
EU	European Union
FID	final investment decision
FPSO	floating production storage and offloading

GASA	general approval for ship application
GCCSI	Global Carbon Capture and Storage Institute
GHG	greenhouse gas
Gt	gigatonnes (10^9 tonnes)
H ₂	hydrogen
IACS	International Association of Classification Societies
ICTN	International Test Centre Network
IEA	International Energy Agency
IEAGHG	International Energy Agency Greenhouse Gas Research and Development Programme
IPCC	International Panel on Climate Change
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
Kg	kilogramme(s)
km	kilometre(s)
LCA	lifecycle analysis
LPG	liquified petroleum gas
MHI	Mitsubishi Heavy Industries
MI	Mission Innovation
MPE	Norwegian Ministry of Petroleum and Energy
MW	megawatts (10^6 watts)
Mt	megatonnes (10^6 tonnes)
Mtpa	million tons per annum (year)
MWh	megawatt-hour(s)
NASEM	National Academies of Sciences, Engineering and Medicine
NCCC	National Carbon Capture Center (USA)
NDC	nationally determined contribution
NET	negative emission technology
NETL	National Energy Technology Laboratory
NH ₃	ammonia
NOK	Norwegian krone
NPC	National Petroleum Council
OGCI	Oil and Gas Climate Initiative
PCI	Projects of Common Interest
PIRT	Projects Interaction and Review Team
POX	partial oxidation
PRD	priority research direction
PV	photovoltaics

R&D	research and development
RD&D	research, development, and demonstration
RFNBO	renewable fuels of non-biological origin
SBCC	ship-based carbon capture
SDE++	Stimulation of sustainable energy production, a Dutch funding scheme
SDG	sustainable development goal (UN)
SDS	sustainable development scenario (by IEA)
SMR	steam methane reforming
SPE	Society of Petroleum Engineers
SRMS	storage resources management system
STEPS	Stated Policies Scenario (by IEA)
t	tonne(s)
T&S	transport and storage company
TEA	technoeconomic analysis
TRL	technology readiness level
TRM	Technology Roadmap
TWh	terawatt-hour(s) (10^{12} watt-hours)
TUC	Trades Union Congress
UK	United Kingdom
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
VR	virtual reality
ZEP	European Technology Platform for Zero Emission Fossil Fuel Power Plants

Annex B. National Strategies

Australia

Hydrogen

<https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf>

Technology Investment Roadmap

<https://www.industry.gov.au/data-and-publications/technology-investment-roadmap-first-low-emissions-technology-statement-2020>

Carbon capture and storage technologies are one of five priority areas for investment under the government's Technology Investment Roadmap. Annual low emissions statements are key milestones of the roadmap process.

Low emissions technology statement

<https://www.industry.gov.au/sites/default/files/September%202020/document/first-low-emissions-technology-statement-2020.pdf>

Canada

Strengthened Climate Plan: "A Healthy Environment and a Healthy Economy"

https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/climate-plan/healthy_environment_healthy_economy_plan.pdf

Canada's Strengthened Climate Plan, released in December 2020, proposes that the government of Canada develop a comprehensive CCUS strategy and explore other opportunities to help keep Canada globally competitive in this growing industry. The government of Canada will connect with partners in other levels of government, industry, and civil society to ensure the strategy is comprehensive, reflects perspectives and opportunities for CCUS across sectors and regions of Canada, and support Canada's 2030 and 2050 energy and climate goals.

Hydrogen Strategy

https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf

Canada's Hydrogen Strategy seeks to modernize Canada's energy systems by leveraging Canadian expertise through building new hydrogen supply and distribution infrastructure and fostering uptake in various end uses that will underpin a low-carbon energy ecosystem. The strategy acknowledges Canada's expertise in CCUS and the key role that carbon capture technologies play in the production of low-carbon-intensity hydrogen. The strategy also recognises the importance of working with international partners to ensure the global push for clean fuels includes hydrogen. The strategy identifies regional opportunities across the country and makes 32 recommendations to lay the foundation and maintain momentum for maximizing the benefits of hydrogen in Canada's energy future.

European Union (EU)

The Hydrogen Strategy

<https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301&from=EN>

By replacing fossil fuels and feedstock in hard-to-decarbonise sectors, renewable and low-carbon hydrogen can contribute to reducing greenhouse gas (GHG) emissions ahead of 2030 and to the recovery of the EU economy, and is a key building block towards a climate-neutral and zero-pollution economy in 2050. Renewable hydrogen also offers a unique opportunity for research and innovation, maintaining and expanding Europe's technological leadership and creating economic growth and jobs

across the full value chain and across the Union. This requires ambitious and well-coordinated policies at national and European levels, as well as diplomatic outreach on energy and climate with international partners. The Commission strategy brings different strands of policy action together, covering the entire value chain, as well as the industrial, market, and infrastructure angles, together with the research and innovation perspective and the international dimension, in order to create an enabling environment to scale up hydrogen supply and demand for a climate-neutral economy. Key actions include:

- Developing an investment agenda through the European Clean Hydrogen Alliance to stimulate the rollout of production and use of hydrogen and build a concrete pipeline of projects.
- Supporting strategic investments in clean hydrogen in the context of the Commission's recovery plan.
- Boosting demand for hydrogen and scaling up production.
- Designing an enabling and supportive framework: support schemes, market rules, and infrastructure.
- Promoting research and innovation in hydrogen technologies.
- Strengthening the international cooperation in international fora for standards and regulations as well as in the next mandate of Mission Innovation (MI2).
- Promoting cooperation with third countries.

France

National Low Carbon Strategy, 2020 (Stratégie Nationale Bas-Carbone, SNBC2)

English version: https://www.ecologie.gouv.fr/sites/default/files/en_SNBC-2_complete.pdf

The revised National Low Carbon Strategy, which was adopted in April 2020, sets out the path to carbon neutrality in 2050, a more ambitious target compared to the initial Factor 4 objective (75% reduction of GHG emissions) set up in the first edition (2015) of this strategy. The revised strategy outlines ways to compensate for irreducible anthropogenic emissions of GHGs with carbon sinks, including natural sinks (forest, soils) and anthropogenic sinks such as CCUS, which is anticipated to reduce 15 MtCO₂/year by 2050. According to the second *Stratégie Nationale Bas-Carbone (SNBC2)*, in 2050, there would be a need for CCS to avoid about 6 MtCO₂/year in industry and produce about 10 MtCO₂/year of negative emissions from biomass energy production plants (BECCS). The SNBC2 recommends initiating today the development and adoption of disruptive technologies to reduce and, if possible, eliminate residual emissions, such as supporting the development of pilot and possibly commercial CCS and CCU units.

In the framework of the economic recovery plan for 2020–2022 (“France Relance”), the French government has chosen to make exceptional investments in sectors/technologies of the future, during and after the recovery: they take the form of unified and global national strategies, activating several levers (fiscal, normative, financial...) and responding to priority innovation needs or market failures. These are the acceleration strategies for innovation for which the State is mobilising 12.5 billion euros over five years through the “Investment for the Future” programme (Programme d’investissements d’avenir – PIA4), part of which is within the framework of the recovery plan. Four strategies of acceleration are already adopted; eleven are under preparation.

<https://www.gouvernement.fr/qu-est-ce-qu-une-strategie-d-acceleration-pia4>

The national acceleration strategy for low-carbon hydrogen, <https://www.gouvernement.fr/strategie-pour-l-hydrogene-decarbone>, was published in September 2020.

The hydrogen strategy sets three objectives:

1. To install enough electrolysers to make a significant contribution to the decarbonisation of the economy.
2. To develop clean mobility, particularly for heavy vehicles.

3. To build an industrial sector in France that creates jobs and guarantees French technological expertise.

The national acceleration strategy for the decarbonation of industry, <https://www.gouvernement.fr/les-strategies-en-cours-d-elaboration>, is being prepared and will be published mid-2021.

The aim is to enable the emergence of decarbonation solutions that create value in the French territory but also to promote their deployment within industry to ensure the sustainability of companies established in France. The strategy will focus both on existing solutions, with the aim of scaling up and deploying them, and on breakthrough solutions for which the challenge is to commercialise, patent, and market an innovative solution. In particular, the following will be targeted: improving the energy efficiency of processes; decarbonizing the energy mix of industrial companies, particularly in terms of heat (in connection with the measures of the France Relance plan); and deploying decarbonated processes and carbon capture, storage, or utilisation.

Germany

The Federal Government's Climate Action Programme 2030

www.bmwi.de/Redaktion/DE/Artikel/Industrie/klimaschutzprogramm-2030.html

The programme comprises several components:

1. Carbon pricing
2. Burden reduction for citizens and industry
3. Sector-specific measures (e.g., increasing energy efficiency and optimising or substituting production processes in industry sectors)
4. Non-sector-related measures such as increasing the production and use of H₂ as well as carbon use and storage

CCS and CCU are considered as measures to reduce otherwise unavoidable industrial emissions. For emissions that cannot be re-used, offshore storage is suggested.

To support the implementation of these technologies, the federal government intends to further support R&D in CCU (and CCS) technologies. The current research framework programme, FONA («Research for Sustainable Development»; www.fona.de), focuses on CCU. For example, in the FONA funding measure Carbon2Chem (2016–2026; <https://www.fona.de/en/measures/funding-measures/carbon2chem-project.php>), the use of real smelter gases to create primary chemicals for fuel, plastics, or fertilizer production is investigated and tested at pilot scale at the thyssenkrupp steel plant in Duisburg.

A national hydrogen strategy (www.bmwi.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.html) was approved on June 10, 2020, in which production and use of green hydrogen are the key elements, while the use of “CO₂-neutral” hydrogen is seen as an interim solution until green hydrogen is available in sufficient amounts. Several regional initiatives are developing and deploying hydrogen production and use networks, e.g., «Westküste 100 real-world laboratory» (www.westkueste100.de/en/) and «Hydrogen and power storage & solutions (HYPOS) East Germany» (www.hypos-eastgermany.de/en/).

Japan

The Long-Term Strategy under the Paris Agreement

<https://unfccc.int/sites/default/files/resource/The%20Long-term%20Strategy%20under%20the%20Paris%20Agreement.pdf>

Japan's Long-Term Strategy under the Paris Agreement was approved by the cabinet in June 2019. The strategy includes a target for CCS: “introduction of CCS by 2030 in coal-fired power generation will be considered, with a view to commercialization”. The document also includes CCU, saying,

“aiming to establish its first commercial-scale CCU technology by 2023 as a trigger for wider usage in view of full social adoption in 2030 and thereafter”.

Strategic Road Map for Hydrogen and Fuel Cells

https://www.meti.go.jp/english/press/2019/pdf/0312_002b.pdf

Japan's latest hydrogen roadmap was published in March 2019 by the Council for a Strategy for Hydrogen and Fuel Cells, a group of experts from government, industry, and academia. The roadmap identifies targets for performance and cost of key hydrogen and fuel cell technologies and actions necessary for achieving these targets. In regard to hydrogen supply chains, the document says, “Japan will try to introduce a full-scale supply chain from manufacturing to transportation/storage of hydrogen based on currently unused overseas energy sources in around 2030”. CCS is included as a key contributor to the establishment of a hydrogen supply chain, the core of which is production and transport of hydrogen from brown coal in Australia.

The Netherlands

The Netherlands includes offshore CO₂ sequestration in the current policy aimed at reducing emissions in the industrial sectors. To incentivize deployment, subsidies are given (SDE++), and a CO₂ bottom price (linked to the EU ETS) is introduced. The first four capture projects put forward their applications for subsidies last autumn, for total claims of EUR 2,1 bln, with an aim to sequester 2.5 Mtpa for 15 years. These projects will use the Porthos backbone for transport and storage.

The Minister's letter to parliament on the applications of the 2020 SDE++ round (Dutch) can be found here:

<https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/kamerstukken/2021/01/14/kamerbrief-over-verloop-openstelling-sde-2020/kamerbrief-over-verloop-openstelling-sde-2020.pdf>

Two transport and storage projects, each targeting a different industrial cluster, are in development. Porthos, which is the most advanced, is located in the Rotterdam Harbour. This project aims to transport and store CO₂ mostly from refineries and chemicals plants. The Athos project is located in the Amsterdam harbour area and is focused on transporting and storing emissions from the steel plant.

Norway

Government White Paper 33 (2019–2020): Longship – Carbon Capture and Storage

<https://www.regjeringen.no/en/dokumenter/meld.-st.-33-20192020/id2765361/>

Although not a strategy per se, the white paper constitutes the technical and economic foundation for realising Longship, a full CCS chain. The Norwegian government intends to contribute to development of CCS technologies and will build on established measures and incentives. The aim is to take CCS technology out into the world, and a prerequisite for the project is international cooperation and follow-up. The government places major emphasis on Longship's being a cost-effective solution for carbon capture and storage and a technology that many can utilise.

The CLIMIT Research, Development and Demonstration Programme for CCS

<https://climit.no/en/>

The CLIMIT programme provides financial support for development of carbon capture and storage (CCS) technology. The programme is aimed at companies, research institutes, universities, and colleges, often in collaboration with international companies and research institutions, which can help accelerate the commercialisation of CCS. The CLIMIT programme is a collaboration between Gassnova and the Research Council of Norway. The Research Council's projects are often referred to as CLIMIT R&D, while Gassnova's part is referred to as CLIMIT Demo.

The Norwegian Government's Hydrogen Strategy toward a Low-Emission Society

<https://www.regjeringen.no/contentassets/8ffd54808d7e42e8bce81340b13b6b7d/hydrogenstrategien-engelsk.pdf>

The strategy sets the course for the government's efforts to stimulate development of hydrogen-related technologies. An important goal for the government is to increase the number of pilot and demonstration projects in Norway by contributing to and supporting technology development and commercialisation. There is a broad commitment to zero-emission technologies and solutions through existing support schemes. The strategy sets out an ambitious policy for zero-emissions solutions in the transport sector, using several institutions to promote it.

Portugal*The Portuguese National Strategy for Hydrogen*

<https://www.portugal.gov.pt/pt/gc22/comunicacao/comunicado?i=estrategia-nacional-para-o-hidrogenio-aprovada-em-conselho-de-ministros>

<https://www.dgeg.gov.pt/pt/areas-transversais/relacoes-internacionais/politica-energetica/estrategia-nacional-para-o-hidrogenio/>

Approved in July 2020, the National Strategy for Hydrogen (EN-H2) proposes a technological path based on renewable electricity, with large amounts being directed to the production of renewable hydrogen and other renewable fuels of non-biological origin (RFNBO), in particular methane and aviation kerosene, as well as of certain chemicals to be used as raw matter by the industry, such as ammonia. For this process of producing RFNBO and other chemicals, carbon dioxide must be added to hydrogen. This CCU aspect stands more implicit than highlighted in EN-H2; however, it is a technical necessity.

EN-H2 includes plans for building a large-scale electrolyser at Sines, running on renewable energy, with a 1 GW capacity until 2030.

The quantities of RFNBO in EN-H2 imply around 1 Mt CO₂ capture by 2030 and around 9 Mt CO₂ by 2050 (essentially for methanation processes). The mix of origins for CO₂ responds to certain criteria: for instance, capture of biomass thermal power plant emissions has the highest priority, as they do not count toward the country's GHG emissions and therefore can be used for assembling RFNBO with no implicit fossil context. On the other hand, emissions from fossil fuels or non-energy processes have the lowest ranking because they lead to just a transitory use of CO₂, which will end up in the atmosphere anyway.

Romania

Romania is committed to reducing greenhouse gas emissions and to making the complete transition to a climate-resilient economy and a greener economy by 2050.

The National Strategy on Climate Change and Low-Carbon Economic Growth

<http://www.mmediu.ro/categorie/strategia-nationala-privind-schimbarile-climatice-rezumat/171>

This strategy shows strategic objectives for reduction of emissions from eight economic sectors (energy, transport, industry, agriculture and rural development, urban development, waste management, water, and forestry). One of the key objectives for the energy sector is to reduce the intensity of CO₂ emissions related to energy through promotion of renewable sources and high efficiency cogeneration.

Within Romania's energy strategy 2019–2030, with the perspective of 2050

(<http://energie.gov.ro/transparenta-decizionala/strategia-energetica-a-romaniei-2019-2030-cu-perspectiva-anului-2050/>), the first strategic objective refers to clean energy and energy efficiency.

CCS can contribute to the achievement of this objective on the pathway to zero emissions from the

energy production sector. Hydrogen is also mentioned as an important energy source, together with the renewable sources that could substantially contribute to the transformation of the energy system.

As a measure of emissions reduction, Romania has implemented the EU ETS Directive and has limited support for large industrial CO₂ emitters. This has raised some interest in CC(U)S in the country, especially now that the regulatory framework for CO₂ geological storage has been prepared. This regulatory framework is based on the implementation of Directive 2009/31/EC for the geological storage of CO₂, transposed into Romanian legislation through Law 114/2013 (representing approval of Government Emergency Ordinance 64/2011). The Competent Authority for geological storage was established as the National Agency for Mineral Resources (NAMR), which also regulates hydrocarbon operations and all the other natural resources of the country. The service for CO₂ geological storage within NAMR has issued specific procedures for granting exploration and CO₂ storage permits. No CC(U)S project is currently under development or in operation in Romania. The only CCS project proposed was the GETICA CCS full-chain demonstration project, selected second on the waiting list of the first NER 300 call. Because of the lack of governmental support and the impossibility of ensuring the funding scheme, the project stalled in 2012.

South Africa

CCS has been identified as one of the CO₂ emissions reduction mechanisms that could assist South Africa with meeting its emissions reduction targets and has been identified as one of the National Flagship Priority Programmes in the National Climate Change Response White Paper.

The initial focus for CCS in South Africa was on geological storage. Without safe and permanent storage, CCS would not be a viable option to mitigate CO₂ emissions. Following the publication of the *Atlas on Geological Storage of Carbon Dioxide in South Africa*, 2010, the South African government, through the South African National Energy Development Institute (SANEDI), initiated a Pilot CO₂ Storage Project (PCSP).

With the PCSP well advanced, other aspects of CCUS are being incorporated into the programme, such as carbon capture, carbon utilisation, and mineral carbonisation.

More recently, the Minister of Mineral Resources and Energy has approved the transfer of the CCUS Programme from SANEDI to the Council for Geosciences (CGS). The major change to the Programme is to site the PCSP in the Mpumalanga Province, closer to the main sources of CO₂ emissions.

South Korea

Hydrogen Roadmap

https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiUyYW1wJ7vAhUxIYsKHfFGCIMQFjAAegQIARAD&url=http%3A%2F%2Fwww.h2eva.org%2Fdownload.php%3Ffile%3D20181112_visualization_of_key_results.pdf&usq=AOvVaw2PX_UfJ95jsioo4nBhdria

Spain

The EU Directive was translated into the Spanish legal framework in 2010: Law 40/2010 of CO₂ geological storage.

Available in Spanish: <https://www.boe.es/eli/es/l/2010/12/29/40>

United Kingdom

The U.K. Climate Change Act 2008 amends the Energy Act 2004 and sets out targets for 2050, including emissions reduction and carbon budgeting. The Climate Change Act led to the establishment of an independent statutory body that sets the carbon budget for the United Kingdom,

the Climate Change Committee. Progress and priorities on CCUS are reviewed by the ministry-led CCUS council.

<https://www.legislation.gov.uk/ukpga/2008/27/contents>

<https://www.theccc.org.uk>

<https://www.gov.uk/government/groups/ccus-council>

Under the Climate Change Act, the UK government launched the Clean Growth Strategy in 2017. Within this strategy, CCUS played a significant role in reducing industrial emissions. During 2020, the government set out a 10-point plan for a Green Industrial Revolution, which was followed by a white paper setting out plans for a net-zero-emission future for the United Kingdom. The envisioned role for CCUS in reaching emission targets was again clearly set out, and a more significant role for hydrogen described.

<https://www.gov.uk/government/publications/clean-growth-strategy>

<https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution>

<https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future/energy-white-paper-powering-our-net-zero-future-accessible-html-version>

The United Kingdom aims to become a global technology leader for CCUS and to ensure viability of the option of deploying CCUS at scale during the 2030s, subject to costs coming down sufficiently. To progress this ambition, the United Kingdom had three main strands: re-affirming commitment to deploying CCUS in the United Kingdom, subject to cost reduction; international collaboration on CCUS; and CCUS innovation. The government continues to work with the ongoing initiatives in Teesside, Merseyside, and Grangemouth to test the potential for development of CCUS industrial decarbonisation clusters.

<https://www.gov.uk/guidance/uk-carbon-capture-and-storage-government-funding-and-support#the-governments-approach-to-ccus>

The United Kingdom is part of MI, CEM, CSLF, and Emissions Reduction Alberta (ERA)-ACT as part of the country's commitment to international collaboration on CCUS. A review of business models that could enable CCUS in the United Kingdom was published in late 2020. National funding for CCUS and hydrogen covers the full range of technology readiness levels, from R&D on innovative new concepts to assessing the feasibility of decarbonisation of industrial clusters and deployment of CCUS projects. Most recently, projects have been invited to request support through the Industrial Strategy Challenge Fund – decarbonisation of industrial clusters deployment. Projects invited through to the second stage focus on decarbonised industrial clusters utilising CCUS and/or hydrogen.

<https://www.gov.uk/government/publications/carbon-capture-usage-and-storage-ccus-business-models>

<https://www.gov.uk/government/publications/call-for-ccus-innovation>

<https://apply-for-innovation-funding.service.gov.uk/competition/498/overview#summary>

<https://www.ukri.org/our-work/our-main-funds/industrial-strategy-challenge-fund/clean-growth/industrial-decarbonisation-challenge/>

<https://www.gov.uk/government/collections/net-zero-innovation-portfolio>

<https://www.gov.uk/government/news/government-unveils-200-million-package-to-help-innovative-businesses-bounce-back>

United States of America

National Summary: CCUS and Hydrogen

Deployment policies and programmes in place:

- 45Q tax credits, loan programmes, and state policies/mechanisms (such as the California low-carbon fuel standard [LCFS])
- Carbon storage regulatory framework in place for enhanced oil recovery and saline storage
- Regional CCUS Deployment Initiative
- Carbon Storage Assurance Facility Enterprise (CarbonSAFE)
- Carbon Capture FEED Studies
- CCUS demonstrations

RD&D priorities going forward:

- Focus on enabling integrated CCUS deployments across multiple sectors and industries
- Capture: R&D for enabling higher rates of capture (>95%)
- Utilization: Continued development and scale-up of promising technologies
- Carbon storage: Optimizing performance, expanding characterization efforts, leveraging machine learning/artificial intelligence
- Negative emissions technologies: direct air capture, biomass with CCS, mineralization
- Hydrogen coupled with CCUS

Useful Links

- Carbon Capture, Utilization and Storage Research at DOE: <https://www.energy.gov/fe/science-innovation/office-clean-coal-and-carbon-management>
- NETL Carbon Capture Program: <https://netl.doe.gov/coal/carbon-capture>
- NETL Carbon Utilization Program: <https://netl.doe.gov/coal/carbon-utilization>
- NETL Carbon Storage Program: <https://netl.doe.gov/coal/carbon-storage>
- DOE Hydrogen Program Plan: <https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf>
- DOE Office of Fossil Energy – *Hydrogen Strategy: Enabling a Low Carbon Economy*: https://www.energy.gov/sites/prod/files/2020/07/f76/USDOE_FE_Hydrogen_Strategy_July2020.pdf