CCUS SET-PLAN

Deliverable 5.9

SUMMARY REPORT ON CCUS INTEGRATION IN ENERGY AND INDUSTRIAL SYSTEMS

MAY 2022

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

Project's name: IMPACTS9. IMPACTS9 is a Horizon 2020 project (Coordinated and Support Action) funded by the European Commission for 3 years (from 1 May 2019 until 30 April 2022). Its purpose is to accelerate the progress realised within the CCUS SET-Plan and to support delivery of the R&I activities in the CCUS Implementation Plan.

https://www.ccus-setplan.eu/

Disclaimer

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS

Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

Table of contents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

Introduction

The report will consider the learnings from the IMPACTS9 project and consider how these fit into the wider EU energy landscape, e.g. a coupled CCUS-renewables energy system to support decarbonisation. This deliverable builds on earlier deliverables in IMPACTS9, available on the CCUS SET-Plan website[1], which are synthesized and complemented with additional analyses and contributions.

The energy landscape has changed significantly during the last years. Only since the start of the definition of the Implementation Plan on CCUS in 2019, major framework plans and reports have been presented, that are of large importance to the energy and industrial systems in Europe, and to the role of CCS and CCU in these systems. Most notably are:

- The European Green Deal presented in December 2019; a roadmap for making the EU's economy sustainable while reaching the goal of climate neutrality by 2050.
- EU's 2030 Climate Target Plan presented in September 2020; strengthening the target for 2030 of reducing EU GHG emissions by at least 55% compared to 1990 levels in order to meet net zero GHG by 2050.
- The REPowerEU plan launched in March 2022; with the overarching goal to make Europe independent from Russian fossil fuels well before 2030.
- IPCC Sixth Assessment Report, and especially the report from Working Group 3 on mitigation of climate change, issued in April 2022.

The two last items are reviewed in Chapter 1, with some main figures from the Green Deal included as a reference. The aim is to see how these recent framework updates might change the role of CCUS in the European energy and industrial systems.

[1] https://www.ccus-setplan.eu/

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

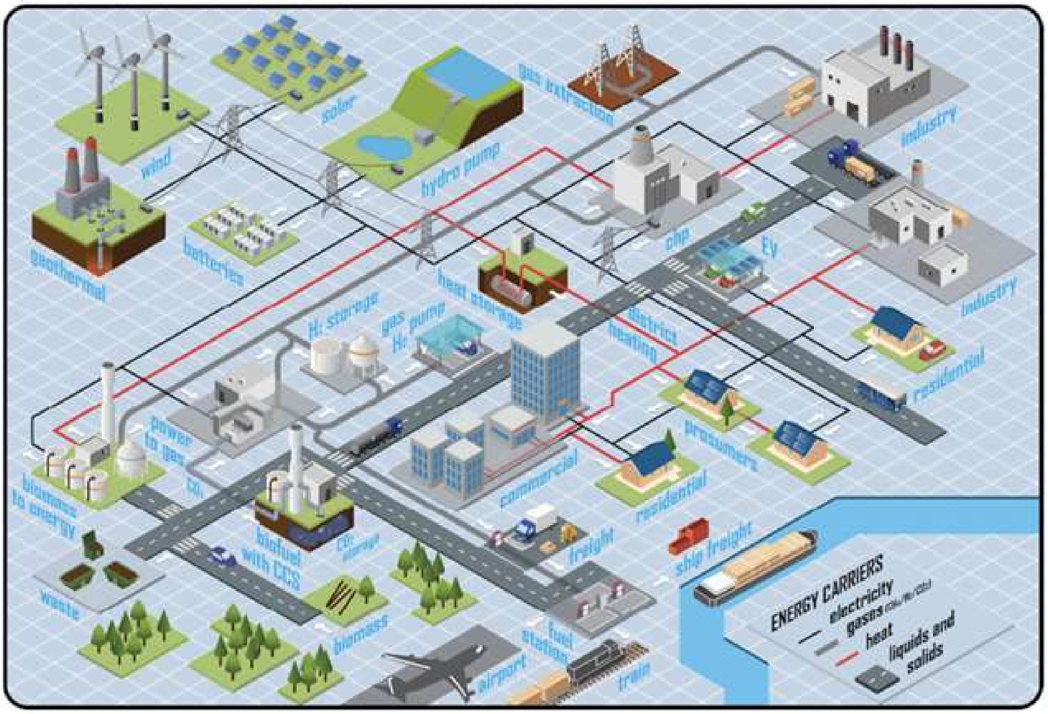

Figure 0-1: Deeply integrated energy system. Figure reproduced from[2]

Future energy systems will be highly integrated systems (see Figure 0-1), where multiple technologies and solutions must be organically deployed across all sectors in order to achieve complete decarbonization.

Chapter 2 clearly highlights the central role that CCUS will play not only in delivering the required GHG emissions reduction but also in forming a sustainable energy system and supporting a low-carbon European economy. To understand how CCUS will be able to fulfil this, the current status of the technology is presented as well as the progress that is needed to ensure effective CCUS deployment.

[2] European Commission (2018). Final report of the High-Level Panel of the European Decarbonisation Pathways Initiative, https://op.europa.eu/en/publication-detail/-/publication/226dea40-04d3-11e9-adde-01aa75ed71a1

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS

Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

Recent updates on relevant aspects of the European energy system

The European Green Deal and 2030 Climate Target Plan

The European Green Deal is a roadmap for making the EU's economy sustainable while reaching its goal of climate neutrality by 2050. It aims at turning climate and environmental challenges into opportunities across all policy areas and making the transition just and inclusive for all[3]. The political momentum generated by the European Green Deal and the legally binding objective of climate neutrality by 2050 have given CCS and CCU strengthened and growing interest from policymakers and industrial stakeholders. CCS and CCU will support Europe's pathway to achieving climate neutrality, enabling a cost-efficient pathway for energy-intensive industries and power plants, safeguarding jobs in core sectors of the EU economy while creating others along the CCS/CCU value chain, and preserving industrial competitiveness[4].

The European Green Deal was presented in December 2019. At that time, the established 2030 target was to achieve at least 40% GHG emissions reduction (compared to 1990 levels), a pathway that would lead to at least 80% GHG emissions reduction by 2050. To meet the more ambitious target of the Green Deal of net zero GHG emissions by 2050, a new EU 2030 Climate Target Plan was presented in September 2020[5]. This implied the new target for 2030 of reducing EU GHG emissions by at least 55%. The accompanying Impact Assessment report[6] evaluated different scenarios for how the European energy system could evolve to meet the GHG targets in 2030 and 2050, and in which sectors to take the most of the GHG reductions.

Figure 1-1 shows the EU sectorial GHG emissions in 2005 and 2015, and projections for 2030 for the most ambitious scenario evaluated in the Impact Assessment report. The energy sectors contribute just over 75% of the total GHG emissions shown for 2005 and 2015. The rest coming from non-energy sector, which includes e.g., process emissions in the industrial sector and non-CO_2 GHG emissions from other sectors than the energy system. Power sector and buildings are the two sectors that must take the largest reduction, 60-70% between 2015 and 2030. Industrial energy emissions will also be significantly reduced, about 35% between 2015 and 2030. CCS and CCU can play important roles in achieving these reductions in the power and industry sector.

Figure 1-2 shows the energy mix of the total energy demand in 2000 and 2015, and projections for 2030 and 2050 for the most ambitious scenario evaluated. The energy mix in 2030 would remain dominated by fossil fuels overall, but renewables increase significantly. By 2050, the trends observed by 2030 are greatly amplified. The growth of renewables is dramatic, more than tripling compared to 2015 (doubling of biomass

[3] https://ec.europa.eu/commission/presscorner/detail/en/ip_19_6691
[4] https://www.ccus-setplan.eu/wp-content/uploads/2021/11/CCUS-SET-Plan_CCUS-Roadmap-2030.pdf
[5] https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1599
[6] European Commission Impact Assessment Report, Stepping up Europe's 2030 climate ambition, Brussels 17.9.2020, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020SC0176

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

and sevenfold increase for other renewables), while fossil fuels (natural gas, oil, and coal in the figure) represent in 2050 only 10-11% of the total energy demand.

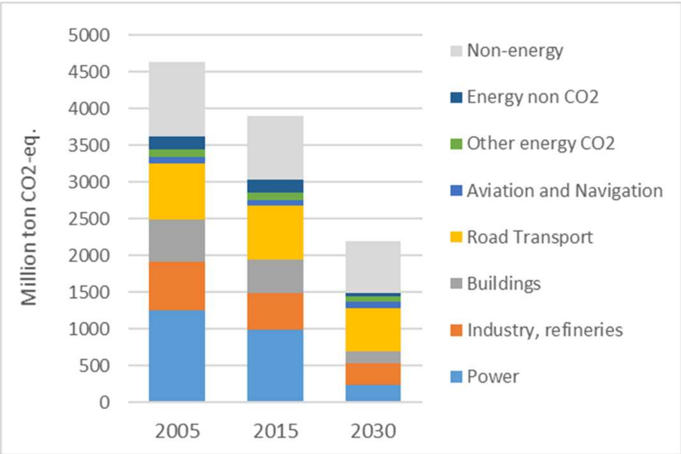

Figure 1-1: EU sectorial GHG emissions in 2005 and 2015, and projections for 2030[6].

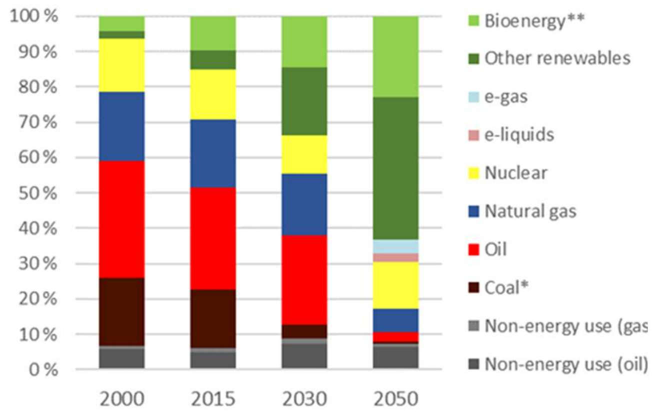

Figure 1-2: EU energy mix for 2000 and 2015, and projections for 2030 and 2050.[6]
*(*includes peat and oil shale, **includes waste)*

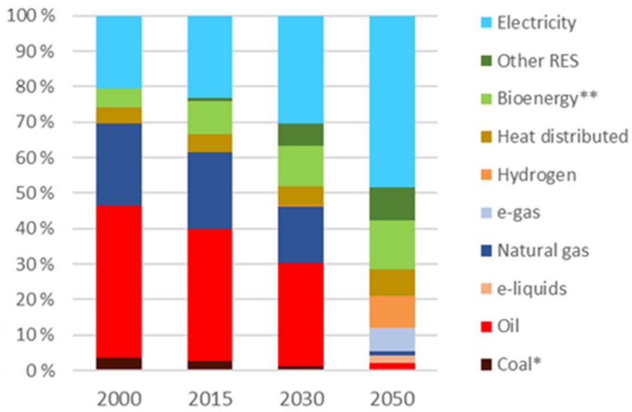

Figure 1-3: Final Energy Consumption by energy carrier[6].
*(*includes peat and oil shale, **solid biomass; liquid biofuels; biogas; waste)*

Figure 1-3 shows final energy consumption by energy carrier. Coal becomes marginal while oil and natural gas remain significant contributors to the final energy consumption in 2030. By 2050, the situation changes radically. Oil and natural gas consumptions are reduced to a fraction in scenarios meeting the 55% target. They are partially substituted by new renewables and low-carbon fuels, mainly of gaseous form and to a lower degree of liquid form. Of the low-carbon gaseous fuels, hydrogen is estimated to cover about 9%, and e-gas about 7%.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

REPowerEU

Considering the Russian invasion of Ukraine, the European Commission launched the REPowerEU plan on 8 March 2022. The overarching goal is to make Europe independent from Russian fossil fuels well before 2030.[7] The plan also outlines measures to respond to the highly increasing energy prices in Europe, and to replenish gas stocks for next winter. The REPowerEU plan will be based on the following pillars[7]:

- Diversifying gas supplies, via higher Liquefied Natural Gas (LNG) and pipeline imports from non-Russian suppliers.
- Larger volumes of biomethane and renewable hydrogen production and imports.
- Reducing faster the use of fossil fuels in our homes, buildings, industry, and power system, by boosting energy efficiency, increasing renewables and electrification, and addressing infrastructure bottlenecks.

The plan is still in discussion with the Member States. It is not a ratified agreement. According to Bellona[8], the plan includes an increase of renewable electricity production of 80 GW, in addition to about 900 GW of solar and wind power already installed and planned (cf. Figure 1-4).

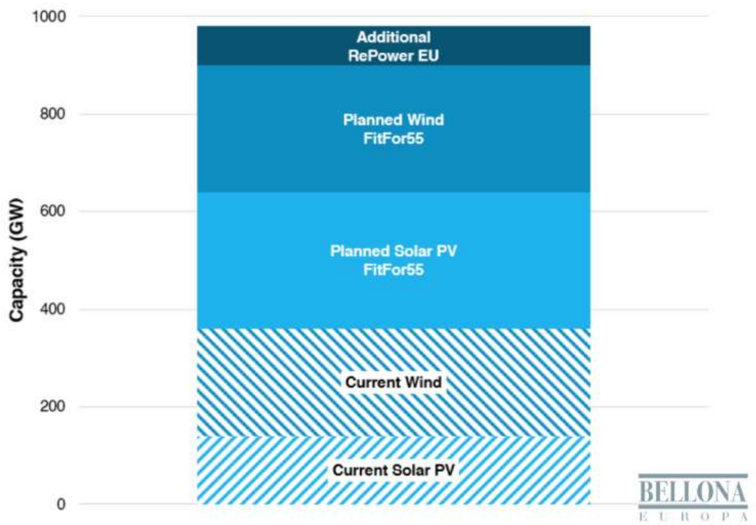

Figure1-4: Installed and planned solar and wind power in EU, plus planned increase through REPowerEU.[8]

Bellona has some considerations about how the renewable electricity should be used in a most efficient way to reduce as much as possible dependency of Russian gas[8]. Their message is that REPowerEU plans for too much green hydrogen production, which they claim to have lower efficiency in displacing gas.

[7] https://ec.europa.eu/commission/presscorner/detail/en/ip_22_1511
[8] https://bellona.org/publication/using-repowereu-to-its-full-potential

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

Bellona analysis shows that a gas power plant using 100% renewable hydrogen would consume 2.8 times the electricity it would produce[9]. Using most of the renewable electricity for direct electrification offers the biggest reduction for gas according to Bellona, and heat pumps are particularly effective at displacing gas demand. A share of the renewable electricity could still be used for hydrogen, to deploy hydrogen economy and ensure a targeted use of hydrogen only in sectors where it is most needed, such as industry and harder-to-abate sectors.

In response to the war in Ukraine, several EU countries have indicated that they have temporarily put their coal phase-out plans on hold and might burn more coal to get less dependent on Russian gas in the short term[10,11]. This will rapidly boost carbon emissions since coal power emissions are twice as large compared to gas power emissions. Czechia, Bulgaria, Romania, Italy, and Germany have indicated they might burn more coal in the short term[11] to reduce their need for gas.

Even though the details of REPowerEU is not fully clear and agreed, there is for sure a strong driver to change the energy system more rapidly than earlier planned. In the present situation it can be expected that the public acceptance for accelerated pace of change will be larger. This might cause an increased acceptance also for technologies and costs earlier being considered negative by the public.

Most likely, the REPowerEU plan will alter the EU energy landscape as it was described through the different scenarios in the Green Deal 2030 Impact Assessment report (cf. this section). In those scenarios meeting the 55% GHG reduction target in 2030, fossil sources (NG, oil and coal) still have a share of 55-57% in the total energy demand (Gross Inland Consumption). Of this, about 20% is natural gas (both energy and non-energy use). This share of fossil sources, and especially gas, can likely be expected to be less as a result of the REPowerEU plan.

What will be the consequences for CCUS technologies in the REPowerEU plan is not clear from the information that can be found. Reduction in fossil sources might also reduce to which extent CCUS technologies will need to be deployed. However, natural gas and oil will still be part of the energy system also in 2030 and 2050, even though considerably reduced, where CCUS could play a role. In the short term it might also be some increase in coal power. And the need for carbon dioxide removal (CDR), which is part of majority of emissions scenarios, will also rely heavily on CCS technologies, being it direct capture from air, from biomass, or from waste with biogenic carbon fraction. And CCU will be an important technology to reach the targeted levels for e-gases and e-liquids (cf. this section).

[9] https://bellona.org/news/renewable-energy/2022-01-leaked-taxonomy-proposal-fossil-gas-sustainable-label-relies-on-promises-in-bad-faith-still-risks-wasting-all-our-renewable-energy
[10] https://www.bbc.com/news/science-environment-60664799
[11] https://www.climatechangenews.com/2022/03/15/some-eu-members-turn-back-to-coal-to-cut-reliance-on-russian-gas/

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

EU greenhouse gas emissions status

The European Environment Agency published in November 2021 an update on EU greenhouse gas (GHG) emissions from 1990 to 2020. The historical trend and future projections are shown in Figure 1-5[12]. The figure also includes the 55% reduction target for 2030 and the net zero target for 2050.

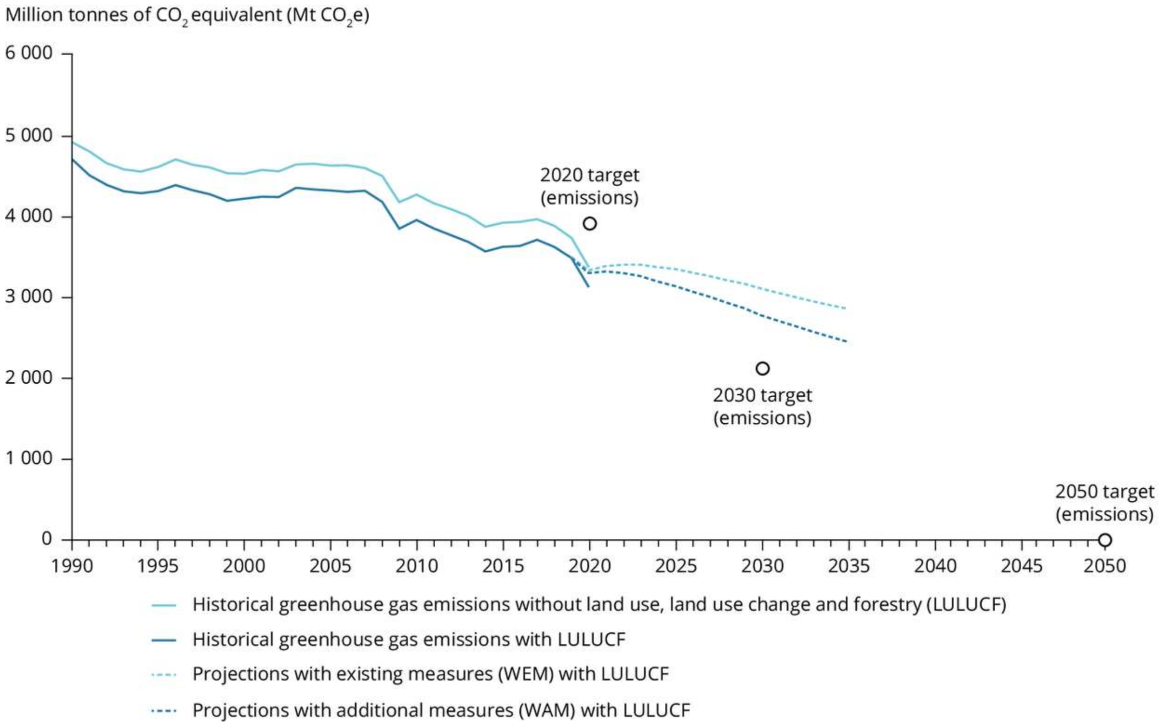

Figure 1-5: Historical trends and future projections of EU greenhouse gas emissions.[12]

GHG emissions decreased by 31% from 1990 to 2020, clearly exceeding the target of 20% reduction. Both 2019 and 2020 saw steep reductions. For 2019 it was mainly due to fossil fuel prices and policy measures, whereas the additional reduction in 2020 was related to the Covid pandemic.[12]

The projections indicate a further decline in GHG emissions to a net reduction of about 41% in 2030. To reach the 55% reduction target, the Member States must update their ambitions accordingly, and more impactful policies and measures across Europe will be necessary to reach this new target.[12]

[12] https://www.eea.europa.eu/ims/total-greenhouse-gas-emission-trends

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

CONTACT DETAILS

Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

IPCC Working Group III report to Sixth Assessment Report

There are now 193 Parties to the Paris Agreement having issued Nationally Determined Contributions (NDCs). The NDCs set the target for greenhouse gas (GHG) cuts and a plan for how to cut emissions and adapt to climate impacts by each Party. 151 Parties communicated new or updated NDCs in November 2021, in conjunction with COP26 in Glasgow. However, quality and ambitions of the NDC's vary, and the present NDCs are still not on track to achieve the goal of the Paris Agreement[13]. See fact box below.

The recent third sub-report to the IPCC Sixth Assessment Report (IPCC AR6 WG3)[14] gives a clear statement saying that "Without immediate and deep emissions reductions across all sectors, limiting global warming to 1.5°C is beyond reach"[15]. Major transitions in energy sector and industry will be needed, involving substantial reduction of fossil fuel use, the deployment of low-emission energy sources, switching to alternative energy carriers, and energy efficiency and conservation.

The report also highlights that a large amount of climate actions is in fact being taken in many countries. Several measures are shown to be effective and if these are "scaled up and applied more widely and equitably, they can support deep emissions reductions and stimulate innovations"[15]. A main message is that there are options in all sectors to halve emissions by 2030.

Fact box: Present global GHG emissions and planned emissions cuts through existing NDCs [14]
(Note: Only median/average values are presented, without the uncertainty limits given in the reference)

- Average annual net anthropogenic GHG emissions during 2010-2019 where higher than in any previous decade.
- Global net anthropogenic GHG emissions in 2019 were 59 GtCO_2-eq. This is 12% higher than in 2010, and 54% higher than in 1990.
- Of the GHG emissions of 59 GtCO_2-eq, about 64% or 38 Gt is CO_2 from fossil fuels and industry. The rest being CO_2 from land use, land use change and forestry, methane, nitrous oxide, and fluorinated gases.
- The two largest GHG emission sectors are energy supply and industry, contributing 34% and 24% of GHG emissions in 2019, respectively.
- Estimated remaining carbon budget for limiting warming to 1.5°C (with > 50% probability) is about 500 GtCO_2, while the estimated remaining carbon budget for limiting warming to 2°C (with > 67% probability) is about 1150 GtCO_2.

[13] https://www.un.org/en/climatechange/all-about-ndcs
[14] IPCC Working Group III report to Sixth Assessment Report, April 2022. Climate Change 2022: Mitigation of climate change. (IPCC AR6 WG3). https://www.ipcc.ch/report/ar6/wg3/
[15] https://unfccc.int/news/the-evidence-is-clear-the-time-for-action-is-now-we-can-halve-emissions-by-2030 (April 4, 2022)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

- In comparison, the estimated cumulative future CO_2 emissions from existing fossil fuel infrastructure (the majority being in power sector) amounts to about 660 $GtCO_2$ if they remain without additional abatement. Including the planned fossil fuel infrastructure, the number increases to about 850 $GtCO_2$.
- Projected global GHG emissions in 2030 when considering the maximum mitigation by NDC's as announced prior to COP26 is 50 $GtCO_2$-eq (min-max 47-55).
- These NDCs do not provide enough GHG emissions reductions. The emission gap between the NDCs and limiting warming to 2°C is in the range 6-14 $GtCO_2$-eq, and in the range 16-23 $GtCO_2$-eq for 1.5°C.

The fact box below summarises the pathways suggested by IPCC to reach the 1.5°C and 2°C targets. It should be noted the larger contribution that is put on carbon dioxide removals (CDR) compared to previous assessments. Bioenergy with CCS (BECCS) and direct air capture (DAC) are modelled to play a significant increased role in many of the emissions pathways limiting global warming to target levels.

Fact box: Emissions cuts needed to fulfil the Paris Agreement [14]
(Note: Emissions reductions given in percentage are in comparison with 2019 level as reference, not with 1990 as reference which is the most commonly used in EU Green Deal and national targets.)

Pathways to limit warming below 2°C (with > 67% probability)

- Net global GHG emissions must peak before 2025, with rapid and deep GHG emissions reductions to follow throughout 2030-2050.
- By 2030, net global GHG emissions must be reduced by 27% compared to 2019 level (i.e., about 16 $GtCO_2$-eq reduction), and by 63% (37 $GtCO_2$-eq) within 2050.
- The related reductions in net CO_2 emissions are 27% by 2030 (~ 10 $GtCO_2$) and by 52% (~ 20 $GtCO_2$) in 2040.
- Global net zero CO_2 emissions are reached about 2070-2075.
- Cumulative net negative CO_2 emissions from 2070-2075 to 2100 are estimated to 40 $GtCO_2$-eq, however, with large variations depending on temperature overshoot and how quickly emissions are reduced.

Pathways to limit warming below 1.5°C (with > 50% probability)

- Net global GHG emissions must peak before 2025, with rapid and deep GHG emissions reductions to follow throughout 2030-2050.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

- By 2030, net global GHG emissions must be reduced by 43% compared to 2019 level (i.e., about 25 $GtCO_2$-eq reduction), and by 84% (49 $GtCO_2$-eq) within 2050.
- The related reductions in net CO_2 emissions are 48% by 2030 (~ 18 $GtCO_2$) and by 80% (~ 30 $GtCO_2$) in 2040.
- Global net zero CO_2 emissions are reached about 2050-2055.
- Cumulative net negative CO_2 emissions from 2050-2055 to 2100 are estimated to 220 $GtCO_2$-eq, however with large variations depending on temperature overshoot and how quickly emissions are reduced.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

Role of CCUS in an integrated energy system

Chapter 1 depicts the future of the European energy system, including the latest updates on the ongoing strategical processes and GHG reduction targets. It sets the overall framework, but it does not discuss how to carry out the necessary energy transition. In this chapter, the integral role of CCUS in the outlined future energy system is discussed. First, the status of CCS and CCU is described. Then the role of CCUS as an essential technology to meet mitigation targets, to form a sustainable energy system and to support a low-carbon European economy is highlighted. The chapter concludes with the progresses needed along the value chain to enable CCUS fulfilling its role. For additional insights into the centrality of CCUS in the European energy transition and into the actions that will be necessary for supporting its large-scale development and deployment, reference should be made to the report "CCUS roadmap to 2030" available on the CCUS SET-Plan website.[16]

Status of CCS and CCU

CCS technologies involve capturing CO_2 produced by large industrial and energy plants, transporting the CO_2, and storing it permanently deep within rock formations or saline formations. For CCU technologies, instead of storage, the CO_2 is used as part of a conversion process, for the fabrication or synthesis of new products, or in non-conversion processes, where CO_2 is used.

From 75 million tonnes a year (Mtpa) at the end of 2020, the capacity of CCS and CCU projects in development grew globally to 111 Mtpa in September 2021. In the GCCUSI Global status of CCUS 2020[17] there are globally 26 projects defined as being in commercial operation today. Only two of these are in Europe, the Sleipner and Snøhvit projects in Norway, which are capturing CO_2 from natural gas streams ("natural gas sweetening"). Those projects have been operational for over 20 years, having stored approximately 1 million tonnes of CO_2 per year since 1996. Most of the operational projects are currently in United States and Canada. However, there are, in Europe alone, 35 projects in development at various stages[18]. Two commercial projects are in the advanced development stage (reaching FEED), namely Fortum Oslo Varme WtE and Norcem cement plant, both being part of the Norwegian Langskip project[19].

Carbon capture technologies can be applied to a variety of carbon dioxide emitting processes: power and heat generation, cement production, iron and steel, waste-to-energy plants, low-carbon hydrogen manufacturing, and other industrial processes. When CO_2 is separated from a stream where parts or all the CO_2 stems from biogenic sources, and is permanently stored, carbon dioxide removal (CDR) is realised. Direct Air Capture, where CO_2 is separated directly from the air, is another CDR technology that has emerged in later times.

[16] CCUS roadmap to 2030: https://www.ccus-setplan.eu/wp-content/uploads/2021/11/CCUS-SET-Plan_CCUS-Roadmap-2030.pdf
[17] Global CCUS Institute, 2020, Global status of CCUS 2020
[18] GCCSI (Global CCS Institute) (2021), Global Status of CCS 2021, https://www.globalccsinstitute.com/wp-content/uploads/2021/10/The-Global-Status-of-CCS-2021-Global-CCS-Institute.pdf
[19] https://CCUSnorway.com/

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

Many different capture technologies have been tested at pilot scale in a lot of national and European research projects. This comprises absorption by liquid solvents, adsorption by solid sorbents, oxy-combustion, membranes, solid looping, low-temperature separation, and others. Absorption by liquid solvents is by far the technology which is most developed and commercially available at a large scale.

Transport of CO_2 is primarily done by pipeline, but other modes of transport, like ship, rail, or road transport, will be increasingly important. The development of shared CO_2 transport infrastructure to connect industrial clusters to storage locations is key to unlock economies of scale on a regional, national, and European level. To meet decarbonisation targets across the EU, it will also be necessary to extend the deployment of CCS and CCU to small emitters and to stranded emitters for which direct connection to pipeline transportation network infrastructure may not be feasible. Crucial for the development of CO_2 networks is the change from point-to-point solution to the creation of hubs and clusters – where CO_2 infrastructure is shared among different emitters.

Permanent and safe CO_2 storage is achieved deep underground, using natural processes that trap CO_2, similar to how oil and gas is trapped for millions of years. Oil and gas fields and deep saline aquifers have similar geological features required for CO_2 storage: a layer of porous rock to store the CO_2 and overlying impermeable layers of cap rock which seals the porous layer underneath, trapping the CO_2. The European Directive on the geological storage of CO_2 provides a regulatory framework that enables storage operators to demonstrate the permanent and safe storage of CO_2 deep underground. Many projects worldwide have now demonstrated that CO_2 storage is safe, technically feasible and cost-effective, with the Norwegian Sleipner project being one of the longest-running projects globally. Now, a portfolio of European storage sites is being appraised and developed, creating a pipeline of storage that will support the first CO_2 capture and transport networks. However, many more storage sites will need to be provided in more regions to enable Europe to achieve its climate mitigation goals. The technical geological CO_2 storage capacity is estimated to be on the order of 1000 $GtCO_2$, which is more than the CO_2 storage requirements through 2100 to limit global warming to 1.5°C[14].

Utilisation is the process of using captured CO_2 in industrial processes or products. CCU technologies are used for the production of everyday products based on CO_2 including building materials, synthetic fuel, chemicals, plastics, and for horticulture. CCU will thus replace incumbent products, decrease reliance on fossil resources, and help to transition to a carbon circular economy. As for all environmental technologies, to determine the climate benefits of each CCU application, full lifecycle analyses (LCA) are required and are becoming available in some areas. Commercialisation of CCU technologies is at an early stage and a series of ongoing and announced projects will reach industrial scale within the next five years.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS

Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

CCS and CCU in Europe in decarbonisation scenarios

The central role that CCS and CCU must play to enable climate ambitions has been confirmed and reinforced by different sources. Completed in 2020[20], the report "Review of Carbon Capture Utilisation and Carbon Capture and Storage in future EU decarbonisation scenarios" shows the analysis of the role of CCS and CCU in the trajectory towards net zero. The synthesis of the publicly available scenarios reviewed stresses that CCS is essential for Europe to reach net zero CO_2 emissions by 2050. In the 1.5°C scenarios, the median CO_2 captured by CCS is 230-430 $MtCO_2/y$ in 2030, increasing to 930-1200 $MtCO_2/y$ by 2050. CCS-enabled carbon dioxide removal (CDR) proved extremely important to reach mitigation targets. The scenarios report a median of CO_2 captured by bioenergy with CCS (BECCS) of 30 $MtCO_2/y$ in 2030, increasing to 400 $MtCO_2/y$ by 2050. [21]

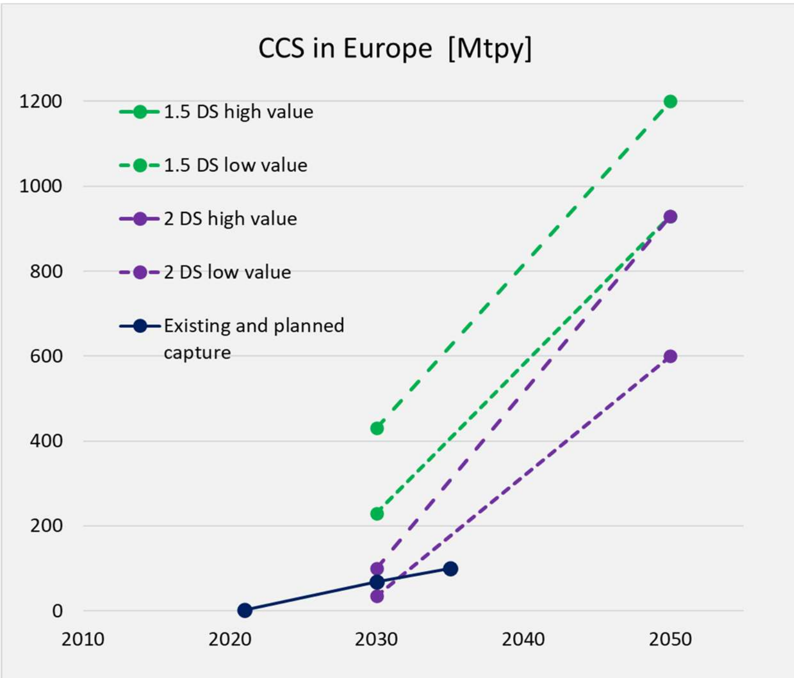

Figure 2-1: Role of CCS in EU as given in[20] for both 1.5°C and 2°C targets (dashed lines). The values in[20] are given only for 2030 and 2050 and the straight lines between are just added here in the figure to visualise the increase. In addition are shown approximate values for existing and planned CCS projects as found in the earlier IMPACTS9 report D3.4.[21]

The range of CO_2 captured by CCS to meet the targets are shown in Figure 2-1, as dashed lines. In the review report, numbers are given only for 2030 and 2050. The straight lines between are just added here to better show the needed increase. High and low values in the figure represent scenarios suggesting high and low

[20] Review of Carbon Capture Utilisation and Carbon Capture and Storage in future EU decarbonisation scenarios, 2020. https://www.ccus-setplan.eu/wp-content/uploads/2021/03/CCUS-SET-Plan_Review-of-CCU-and-CCS-in-future-EU-decarbonisation-scenarios_09.2020.pdf

[21] IMPACTS9 project report: D3.4 Recommendations on the steps required to deliver the R&I activity 6: Developing next-generation CO_2 capture technologies, December 2021.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

level of CCS deployment, respectively. In addition, the ongoing and planned CO_2 capture capacity are added (full line). The figures are taken from an overview of commercial scale CO_2 capture projects in Europe until about 2035. This is an update of the overview of European CCUS projects that can be found on the ZEP homepage[22].

If all what is planned will be realised, the required figures for the 2°C scenario in 2030 can be met, but it is far from meeting the 1.5°C scenario. It is not likely that all the planned projects on this list will be realised. The current trajectory would also lead to CCUS falling short of meeting its targets in 2050. Therefore, it is essential to see many more commercial projects to evolve in the next years until 2030, and a huge increase in commercial scale CO_2 capture capacity from 2030 onwards to 2050.

The IPCC analysed several pathways that limit global warming to 1.5°C in its special report from 2018[23]. In those pathways, a median of around 15 Gt CO_2 is captured using CCS and CCU in 2050. CCS and CCU have a particularly important role in decarbonising hard-to-abate industrial sectors, where emissions reductions by energy and process efficiency would not be sufficient to meet mitigation targets. Importantly, all pathways that limit global warming to 1.5°C with limited or no overshoot rely on CDR. CO_2 emissions captured and stored from bioenergy with carbon capture and storage (BECCS) reaching a median level of 5 Gt CO_2 in 2050. Although showing smaller absolute numbers, the International Energy Agency (IEA) report "Net Zero by 2050[24]" echoes the conclusions by the IPCC. The report foresees that a total of 2.4 Gt CO_2 is captured from the atmosphere by 2050, of which about 80% is permanently removed through a combination of BECCS and DACCS, while the remaining CO_2 is used to provide synthetic fuels.

Recently, IPCC has released its Sixth Assessment Report where there is a wide recognition that CCS and CCU will have a role to play in several sectors[25]. The extent to which CCS is deployed varies between the different emissions pathways. Nonetheless, it is viewed an integral component in achieving the rapid and deep GHG emissions reductions needed to limit the global warming: "Modelled mitigation strategies include transitioning from fossil fuels without CCS to very low- or zero-carbon energy sources such as renewables or fossil fuels with CCS, demand side measures and improving efficiency, reducing non-CO_2 emissions, and deploying carbon dioxide removal (CDR) methods to counterbalance residual GHG emissions"[14].

CCS for carbon dioxide removals (CDR) is a topic that has received significant revision compared to previous assessments. Bioenergy with CCS (BECCS) and direct air capture (DAC) are modelled to play a significant increased role in many of the emissions pathways limiting global warming to target levels.

- In modelled 1.5°C pathways that report CDR, global cumulative CO_2 removal during 2020-2100 is estimated to be 30-780 $GtCO_2$ for BECCS and 0-310 $GtCO_2$ for DACCS.

[22] https://zeroemissionsplatform.eu/about-CCUS-ccu/css-ccu-projects/
[23] IPCC (Intergovernmental Panel on Climate Change) (2018), Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels, IPCC, https://www.ipcc.ch/sr15/
[24] IEA (International Energy Agency) (2021), Net Zero by 2050. A Roadmap for the Global Energy Sector, IEA, https://www.iea.org/reports/net-zero-by-2050
[25] https://zeroemissionsplatform.eu/ipcc-sixth-assessment-report-climate-change-2022-mitigation-of-climate-change/

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

- The same figures in 2°C pathways are 170-650 $GtCO_2$ for BECCS and 0-250 $GtCO_2$ for DAC.

There is a large span in modelled CDR values due to assumptions about costs, availability, and constraints. However, on average the extent of CDR deployment will be large and implementation challenges such as pressure on land and biodiversity are important issues to consider.

The climate contribution of CCU remains unclear, as the carbon footprint is not extensively quantified in modelling and scenario building[26]. Some available scenarios foresee a significant role while others do not consider it. CCU technologies have the potential to contribute to emissions reduction, avoid generating new emissions by reusing existing emissions, and, in certain pathways, to also store CO_2 in a manner intended to be permanent. It is estimated that, by 2050, CCU could reuse up to 7 Gt of CO_2 for the production of fuels, chemicals, and materials[27].

In the Impact Assessment on 'Stepping up Europe's 2030 climate ambition'[28], the European Commission found that it is critical that CCS and CCU are deployed and tested at the industrial scale during this decade. Identifying key enablers and existing barriers for the scale up of CCS and CCU is thus important to create the right economic conditions and a favourable policy framework to enable investments in CCS and CCU.

CCUS integration into future energy systems

CCUS is a fundamental technology to allow the transition towards a future sustainable energy system, which will be based on renewable energy sources. However, the role of CCUS should not be limited to a transition technology. On the contrary, it is clear from the previous section that the effective integration of CCUS into the energy system is necessary to reach net zero CO_2 emissions by 2050, hence, to be in line with the 1.5°C scenario. Indeed, IEA[29] argued in its flagship report "CCUS in clean energy transitions" that reaching net zero will be virtually impossible without CCUS. Future energy systems will be highly integrated systems, where multiple technologies and solutions must be organically deployed across all sectors in order to achieve complete decarbonization. CCUS is a key technology in this regard as it can play a very important role in the deployment of several energy vectors as well as in the decarbonization of hard-to-abate sectors.

In the following, some cross-thematic areas are presented where the importance of CCUS within future energy systems is clearly highlighted.

Industrial decarbonisation

CCUS will play an especially important role in the industrial sector. Industry presents significant challenges to reduce emissions down to zero and beyond, while remaining competitive. Energy efficiency and electrification can only deliver partial decarbonization of the industrial production but fail to deliver net zero

[26] Detz and Zwaan, 2019; Bogdanov et al., 2019; EU Reference Scenario 2020 ; Ram et al., "Powerfuels in a Renewable Energy World - Global volumes, costs, and trading 2030 to 2050", 2020.
[27] Hepburn et al., 2019
[28] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2020:562:FIN
[29] IEA (International Energy Agency) (2020), Energy Technology Perspective 2020. Special Report on Carbon Capture Utilisation and Storage. CCUS in clean energy transitions, IEA, https://www.iea.org/reports/ccus-in-clean-energy-transitions

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

emission from industry. In particular, there exist hard-to-abate industries where CCUS is virtually the only technology solution for deep emissions reductions (e.g., cement production).

The strategic development of CO_2 infrastructure is vital to ensure the large-scale decarbonisation of European industrial sectors, while continuing to invest in the scale up of renewable energy sources. CO_2 transport and storage infrastructure is also instrumental in delivering early, large-scale volumes of low-carbon hydrogen produced from reformed natural gas with CCS, which will enable many industrial processes to be redesigned to avoid CO_2 emissions.

Net-zero CO_2 emissions from the industry sector are challenging but possible through new production processes using low emissions electricity and low-emissions hydrogen and fuels, and through carbon management. The use of steel, cement, plastics, and other materials is increasing globally. For many of these materials, low-emission production processes are at the pilot to near-commercial stage but not yet established industrial practice[14]. Introducing these new processes can increase cost which is an implementation challenge since many of the basic materials industries are exposed to international competition[14]. Hydrogen direct reduction for primary steelmaking is near-commercial in some regions. Other industries, as cement and lime, will have to rely on CCS. Several options are relevant within chemicals production and use, among them fuel and feedstock switching, and carbon from biogenic sources by CCU or direct air capture, as well as CCS[14].

Hydrogen production

The recent report from the *Hydrogen 4 Europe* project showed that hydrogen will play a major role in the decarbonization of the energy sector[30]. The pathways to net zero showed the complementarity between renewable-based and CCUS-based hydrogen production. While low-carbon hydrogen plays a critical role in establishing a hydrogen economy in the first half of the outlook period, renewable hydrogen develops mainly in the second half of the outlook period and meets the bulk of the additional demand growth. Similar considerations are made by IEA in its report "The Future of Hydrogen[31]", where the importance of building on the existing industrial hydrogen infrastructure is stressed. Harnessing this existing scale requires the capture of CO_2 from hydrogen production from fossil fuels in parallel with increasing supplies of hydrogen from clean electricity.

A clean hydrogen economy will therefore initially rely on large volumes of clean hydrogen produced from natural gas with CCS. The development of low-carbon hydrogen is highly dependent on the parallel deployment of the CCUS value chain. Therefore, the development of cross-border CO_2 infrastructure is essential[32]. The initial investment in 'blue' hydrogen production and associated infrastructure – linking this

[30] Hydrogen 4 Europe (2021), Charting pathways to enable net zero, https://www.hydrogen4eu.com/
[31] IEA (International Energy Agency) (2019), The Future of Hydrogen, https://www.iea.org/reports/the-future-of-hydrogen
[32] Material Economics, Industrial Transformation 2050. Pathways to Net-Zero from EU Heavy Industry, 2019

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

clean energy carrier to the customer – will pave the way for the scaling up of green hydrogen, as renewable electricity becomes more abundant.

Carbon dioxide removal

The IPCC Sixth Assessment Report clearly stresses the importance of CDR in future energy systems. A wide deployment of CDR serves multiple purposes. It increases the rate at which we reduce emissions, allowing to approach the required trajectory toward net-zero energy systems. Importantly, CDR further enables offsetting residual emissions from hard-to-abate sectors. This is the case, for instance, of certain industries or of agriculture, where a net-zero balance of GHG emissions is inherently challenging. Without CDR it would be virtually impossible to achieve and retain the net-zero target. In the long-term, the negative emissions delivered by CDR could also contribute restoring the global carbon budget. Hence, the role of CDR as a cornerstone of future energy systems.

Several CDR approaches exists. Some approaches mimic natural processes, such as afforestation and soil-carbon sequestration. Those are well known methods – as they have been practiced for decades to millennia – and will have an important role in pathways towards climate neutrality. However, they alone cannot deliver the extent of emissions removal required. In addition, they act on a rather long timescale, while the need for negative emissions is pressing. Hence, they need to be complemented by other methods, which heavily rely on CCS technologies. The two main options, although not the only ones, are bioenergy with CO_2 capture and storage (BECCS) and direct air CO_2 capture and storage (DACCS). Such technologies give substantial contributions in both 1.5°C and 2°C pathways (see this section) and are expected to be deployed at scale in the future. Hence, the need for CDR in future energy system translates in the need for CCS, on which important CDR approaches rely on.

Energy system integration

The strategic development of CO_2 infrastructure is vital to ensure the large-scale decarbonisation of European industrial and energy sectors, while continuing to invest in the scale up of renewable energy sources. When applied to renewable gases, CCUS is likely to play a role in a climate-neutral energy system, in particular for the decarbonisation of energy-intensive industries.

The future energy system will involve a growing share of renewable energy sources. In the global modelled pathways limiting global warming to 2°C or 1.5°C, almost all electricity supplied in 2050 is from zero- or low-carbon sources, such as renewables, or fossil fuels with CCS, combined with increased electrification of energy demand[14]. This poses challenges of dispatchability. There is a general lack of understanding regarding the importance of power system operation and load control. Flexible dispatchable energy generation technologies such as thermal power with CCS offer a cost effective way to balance the expected intermittency of renewable power generation. Therefore, CCUS can plan a vital role for clean flexible energy generation[33].

[33] IEA (International Energy Agency) (2017), Valuing Flexibility in CCS Power Plants, IEA, https://ieaghg.org/conferences/pccc/2-uncategorised/846-2017-09-valuing-flexibility-in-ccs-power-plants

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

Net-zero energy systems will comprise several measures, including CCS on remaining fossil sources. Limiting global warming to below 2°C will leave a substantial amount of fossil fuels unburned and could strand considerable fossil fuel infrastructure. The value of these has been projected to be in the range 1-4 trillion dollars from 2015-2050. CCS could allow fossil fuels to be used longer and reduce stranded assets. Retrofitting existing installations with CCS, switching to low-carbon fuels (such as hydrogen and its derivatives), and cancellation of new coal installations without CCS are measures that can help bring future power sector emissions in line with modelled least-cost pathway[14].

Circularity and raw materials dependence

Circular economy is one of the pillars of the European climate strategy. CCU technologies have the potential to deliver on the principles of circularity. CCU covers a large set of innovative processes that can recycle CO_2 into valuable products, such as organic compounds, chemical building blocks, synthetic fuels, and building materials. In essence, CCU is circular economy applied to carbon. Overall, a fully circular carbon economy can emerge where CO_2 is no longer considered as a waste emission but as a carbon source in replacement of fossil feedstock.

CCS and CCU to support a low-carbon European economy

The previous sections outline the essential role that CCUS should play in an integrated low-carbon European economy. Given the critical importance of CCUS in enabling Europe's decarbonisation, especially of energy-intensive industries, the rapid deployment of CO_2 transport and storage infrastructure to support these important sectors is a matter of priority. The European Commission should especially support projects that will underpin the development of cross-border CO_2 transport, usage and storage infrastructure, thereby supporting projects along the CCS and CCU industrial chain. The strategic development of CO_2 infrastructure is vital to ensure the large-scale decarbonisation of European industrial and energy sectors, while continuing to invest in the scale up of renewable energy sources. A failure to provide such enabling infrastructure in the short term will increase CO_2 liability risk and undermine investments in jobs and economic activity.

Reaching climate neutrality by 2050 requires strategic investment decisions, even more so as Europe deals with the aftermath of the COVID-19 health and economic crisis. The pathway towards climate neutrality will bring about a major transformation of energy-intensive industries, such as cement, lime, steel and chemicals, that are at the core of the European economy and provide products that are at the heart of how we live our lives. For these sectors, pathways including CCS and CCU represent the lowest-cost route to decarbonisation whilst maintaining industrial activity[34] and preserving existing jobs. It can capture, reuse and store emissions produced during industrial processes, and it also plays an important role in the manufacturing of clean hydrogen, which can be used to fuel energy-intensive industries and households. When applied to industrial processes and power plants, CCS can secure jobs and incomes and ensure European industrial competitiveness in international markets, while delivering sustainable growth.

[34] Zero Emissions Platform, "Climate Solutions for EU industry", 2017

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

Parallel to the storage of CO_2, industry may look into the commercial use of CO_2 for low carbon products, provided that a thorough life-cycle analysis is conducted. While several CCU applications, in many cases, have a limited potential for CO_2 abatement at scale, they could provide a valuable means of incentivising investment in enhanced CO_2 capture technology in the short term, reducing costs for industry and society. Any CO_2 reduction allocation needs accurate carbon accounting covering all processes involved, including e.g. energy inputs and embedded emissions.

Upon an accurate carbon accounting and life-cycle analysis, these solutions should be combined to enable large-scale permanent storage for captured CO_2 to meet the required level of reductions, thus enabling the long-term sustainability of energy-intensive industries in a low carbon Europe.

CCUS will help both the retention of existing jobs and create new jobs by supporting the gradual yet irreversible decarbonisation of European energy-intensive industries that will be impacted by climate change and the economic crisis. By providing a low-carbon alternative, existing jobs in industries – such as cement, steel, lime, and chemicals – will be preserved. Ultimately, CCUS can enable European industrial regions to remain competitive in a net-zero landscape.

Progress needed to ensure CCUS effective deployment

Currently, global CCS deployment is far below what is modelled in pathways limiting global warming to 1.5°C or 2°C. In order to meet the European climate objectives for 2030, more operational CCS and CCU projects at commercial scale are needed. In many project lists, projects at different stages of progress are mixed. Some are ongoing, whereas others are at a planning stage and final investment decisions are not yet taken. Full-scale commercial CCS projects will require all the parts of the value chain to be operational. The elements of the chain, i.e. capture, transport and permanent storage, must be developed and implemented in phase with each other. To do so a series of enablers and hurdles must be carefully considered to ensure conditions for the effective roll-out of the required value chains.

In this section, an overview of key technical, political, financial and social acceptance barriers is provided. For a more insights, a dedicated report was developed and is available on the CCUS SET-Plan website[35].

Technical development and R&I needs along the value chain

Needs and progress needed is reported for the different element of the CCUS value chain.

Capture

- Capture technologies should be developed to enable high capture rates (>95%) and CDR schemes. The development of a clear and shared framework for carbon accounting and for guaranteeing the sustainability of bioresources is fundamental to enable CDR solutions.

[35] https://www.ccus-setplan.eu/wp-content/uploads/2021/03/CCUS_SET-Plan_Key-enablers-and-hurdles-for-CCUS-deployment_11.2020.pdf

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

- The energy requirements for the CO_2 capture process are important factors to identify a suitable match between capture technology and industrial application. Technology development should be guided by considerations of accessibility to clean and sustainable energy sources.
- Other technical aspects should be given importance, such as flexibility, compactness, and potential for heat integration and process intensification.
- Technological advancements are needed for the development of novel reactor designs, modularisation, and cost-effective materials.
- Cost reduction can be pursued both in terms of CAPEX and OPEX. The development of a funnel of large projects, based on CO_2 capture technologies at different high Technology Readiness Levels (TRL), will contribute to bring down costs.
- The formation of industrial clusters should be supported as they offer opportunities for energy integration, sharing of common infrastructure, and risk reduction for each cluster partner.
- Control of emissions and other health, safety, and environmental considerations are critical for reaching commercialisation of capture technologies. As such, they should be addressed early in the development of new technologies.
- Next generation CO_2 capture technologies must guarantee the quality and continuity of the industrial production or process where they are applied (for example via technology qualification).
- The development of a stable framework to enable early movers is essential to create the conditions to achieve climate goals: standards, funding and incentives, risk sharing, and business models. It is particularly important to support projects whose implementation contributes to developing a CCS and CCU network, for instance capture projects that will feed large transport and storage infrastructure projects (e.g. the Northern Lights/Longship project in Norway, which is the first European, commercial, full-chain CCS project to become operational).

Transport

- Value chain analyses (full chains, H_2, ammonia and liquid organic H_2 carriers)
- New CCS and CCU chain concepts and transport networks (including hubs, buffers)
- Impact of CO_2 composition and impurities
- Safety assessments and engineering design tools
- Non-pipeline transport of CO_2 (e.g. ships, rail, trucks, etc.)
- Injection of fluctuating CO_2 flows, particularly into low pressure reservoirs
- Improved understanding of thermophysical properties of CO_2 and CO_2 mixtures.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

Storage

- Appraisal of storage regions which would include pre-competitive evaluation of storage options to encourage subsequent commercial project uptake.
- Although the feasibility of CO_2 storage has been established for decades, storage characterisation should include the testing of new formations to assess their feasibility for storage, which may be particularly important in onshore locations and for testing in saline aquifers, including management of produced waters. Enabling onshore CO_2 storage, through demonstration of technical and safe feasibility in test injection projects, which openly addresses the concerns of communities, will allow more rapid and lower-cost CCS deployment.
- Regulatory requirements for monitoring plans, especially following site closure, should be flexible and adaptable to take account of site-specific pressure regimes and containment processes. For example, storage in pressure-depleted gas fields may not require any postclosure monitoring and therefore may offer lower cost solutions.
- Innovation to reduce costs of CO_2 storage operations, including reducing risks and uncertainties, reducing development and operational costs through e.g. innovative monitoring, drilling and asset management.

Utilisation

- Further development of novel, durable and cost-effective materials for capture
- Novel catalysts for catalytic conversions, based on abundant raw materials
- Development of integrated capture and conversion systems
- Optimisation of process conditions for increased CO_2 uptake rates
- Metrology protocols and methodologies for accurate measurements of concentrations and quality of CO_2 streams
- Inclusion of CCU pathways in models and scenarios of future energy and industrial systems
- Non-technological assessments such as systematic Life Cycle Analysis, Techno-Economic Assessment studies, and comprehensive social acceptance studies.

Barriers and progress needed within policy and regulation

The following recommendations are proposed that would help overcome key barriers within policy and regulations and deliver a policy framework to ensure cost-efficient industrial decarbonisation, attract further industrial and private investments in CCS and CCU, and raise awareness of the multiple climate benefits of these technologies.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS

Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

- The European Commission should propose as soon as possible a European CCS and CCU strategy, setting out the foundation for a European, low-carbon CCS and CCU industry and a vision and objectives to be achieved.
- Use the National Energy and Climate Plans (NECPs) and the industrial transition pathways coming out of the EU Industrial Strategy as a basis to draft decarbonisation pathways and highlight the role of CCS and CCU. The sector-specific voluntary roadmaps envisaged under the European Climate Law offer opportunities to create synergies with the transition pathways under the Industrial Strategy.
- EU member states should be strongly encouraged to ratify the amendment to article 6 of the London Protocol, therewith effectively simplifying the legal and administrative work associated with export of CO_2 for permanent offshore storage.
- EU member states should be encouraged to implement complementary policy mechanisms on a national level to support the scale-up and deployment of CCS and CCU technologies
- In the upcoming communication on a regulatory framework for carbon dioxide removals, the European Commission should set out clear definitions and a plan to incentivise CDRs, based on robust carbon accounting and full life-cycle analysis.
- The capture of biogenic and atmospheric CO_2 should be incentivised.
- Priority regions for appraisal should be identified, using the proposed online open-access European Storage Atlas as a foundation and establishing recommendations and responsibilities for development.
- The sharing of good practice in these areas should be supported to enable all European regions to benefit from these early developments.

A framework for funding CCS and CCU

During this decade, it is crucial to put in place the policy and regulatory framework for the large-scale deployment of CCS and CCU technologies, making the technologies investable. While the mitigation role of CCS is demonstrated and acknowledged by several modelling scenarios, securing broad political support for the technology has been a barrier for large-scale CCS projects in the early 2000s. It is crucial to build awareness and political support in this decade to ensure the necessary scale-up. Funding for CCUS R&I plays an important role in this picture, as research and innovation are key actions towards a climate neutral and competitive Europe.

The EU should set the foundations for a transition towards a climate-neutral economy and incentivise decarbonised industrial products. Introducing public procurement standards and further market-pull mechanisms are examples of how to encourage the uptake of low-carbon products. Coupled with a functional

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CO_2 price, this should enable the CCS and CCU industry to become self-sustainable in the long-term after the initial support mechanisms that are needed to demonstrate technologies at a large scale in Europe.

- National funding should complement and be synchronised as much as possible with funding at European Union level. Instruments such as the Recovery and Resilience Facility should be utilised to promote the greener transformation of different economic sectors, thus the inclusion of CCS and CCU in national recovery plans is critical.

Social acceptance challenges

As CCS and CCU projects come closer to becoming operational, there is a need for 'capacity building' at the level of local governments in order to be able to provide regulatory guidance for CCS and CCU projects. Activities to improve the knowledge and expertise about CCS and CCU projects should be carried out and be aimed at local and regional officers.

In general, there is limited awareness of the value and benefit of CCS and CCU technologies. When presented with neutral information on CCS, people favour other mitigation options such as renewable energy and energy efficiency. Specific CCS projects have faced strong local resistance, which has contributed to the cancellation of CCS projects [14]. In the next decade, it will be important to build a positive message around the climate benefits of CCS and CCU, describing how these technologies work and highlighting how they are relevant to the everyday lives of EU citizens.

It is equally necessary to bring together policymakers at local, regional, national, and EU levels with companies and other societal actors, such as trade unions and environmental NGOs, to engage in a transparent dialogue on the benefits of CCS and CCU projects for communities.

At EU level, the European Commission has a good opportunity to increase the understanding around CCS and CCU with initiatives such as the CCUS Forum, which should continue on a yearly basis. This Forum provides an opportunity to bring together stakeholders from different groups to learn more about CCS and CCU and highlight the challenges that they encounter and the value and benefits that these technologies can bring.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 842214

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS

Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium