Deliverable 3.7

RECOMMENDATIONS ON THE STEPS REQUIRED TO DELIVER R&I ACTIVITY 7: CCU ACTION

JANUARY 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.

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Table of contents

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Overview of Carbon Capture and Utilisation

Carbon Capture and Utilisation (CCU) represents an array of technologies that capture CO_2 from point sources (for example industrial installations) or directly from the air and use it directly or convert it into a wide spectrum of marketable products for energetic (fuels) and non-energetic uses (chemicals or materials). This report will not go into a detailed listing and description of CCU technologies; the reader is referred to the following indicative sources for a more detailed overview of the multitude of CCU pathways:

- The 2018 report of the Science Advice for Policy by European Academies (SAPEA): "Novel CCU technologies"
- The 2019 report of the National Academies of Science, Engineering and Medicine (NASEM): "Gaseous Carbon Waste Stream Utilization"
- The 2019 report of the International Energy Agency (IEA) "Putting CO_2 to use" as well as further technical reports of the IEA GHG R&D programme, for example the 2021 study "CO_2 as a Feedstock: Comparison of CCU pathways"
- The 2021 report of the EU funded project ECCSELERATE "Global CCU Infrastructure market assessment"
- The 2021 "CO_2 Utilisation Roadmap" from the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia

This report provides a broad overview of the concept behind CCU and focuses mostly on the current progress on achieving the CCU targets within the CCUS Strategic Energy Technology Plan (CCUS SET Plan). CCU can be graphically represented in the following figure:

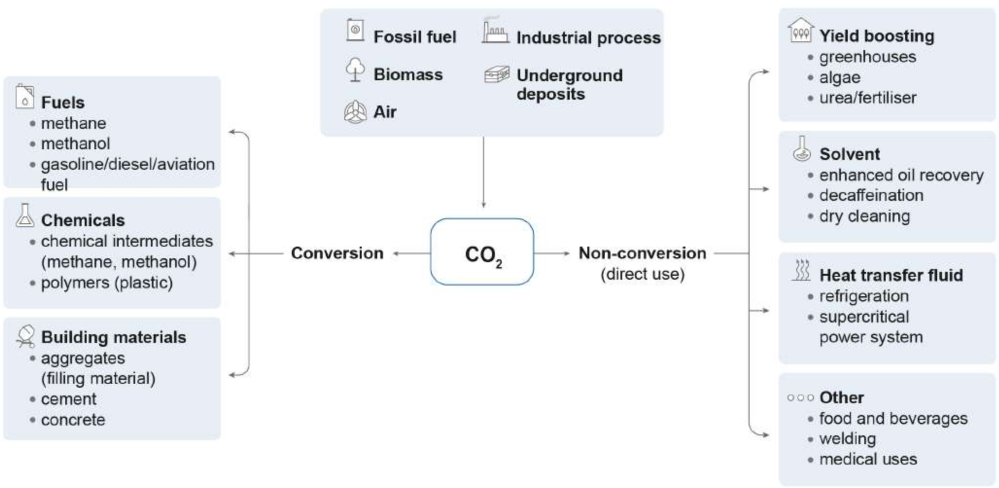

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Figure 1: Classification of CO_2 uses (from IEA, 2019, "Putting CO_2 to use")

The sources of CO_2 can be broadly separated in 4 basic categories: (i) CO_2 from fossil origin, i.e. CO_2 emitted from the combustion of fossil fuels, (ii) CO_2 from biogenic origin, i.e. CO_2 emitted from biological processes and the treatment of biomass, for example bioethanol, biogas or bioenergy production, (iii) CO_2 from industrial processing, for example CO_2 from processing limestone into lime or from steel furnaces, (iv) CO_2 from the atmosphere. It is expected that, as the transition to more renewable energy systems will continue in the years to come, CO_2 from fossil origin will not be prevalent and the other sources of CO_2, atmospheric, biogenic and unavoidable process will be the main sources in the years to come. Capture processes at different levels of technology maturity have been developed for all existing sources of CO_2, both from industrial sources (often referred to as point sources) and from the air (i.e. Direct Air Capture, DAC). The technical specificities and requirements of the capture processes will be determined to a certain extent by the quality of CO_2 required in the subsequent utilisation pathways and the type and level of impurities that these pathways can tolerate.

Utilisation of CO_2 may not require transformation of the molecule (e.g. direct use of CO_2 in beverages, in greenhouses, or as technological fluid in industrial processes). To be noted, the use of CO_2 for Enhanced Oil Recovery (EOR) is not under the scope of this report. Most commonly, CCU is associated with transformation of CO_2 into another product through an array of industrial processes. The basic classes of products from CCU are fuels, chemicals and materials. When the final product is a fuel or a chemical molecule, the process is usually involving the reaction of CO_2 with an energy carrier (renewable hydrogen) in a (bio-)catalytic process, for example thermochemical hydrogenation, electrochemical reduction, photocatalytic conversion, biological conversion. Products from such processes are molecules like methanol, methane, ethanol, formic acid, ethylene, light hydrocarbons that can directly replace conventionally produced, fossil-based equivalents. Often, specific catalysts allow the direct incorporation of CO_2 into the final product without prior conversion (e.g. production of CO_2-based polyols). Contrary to fuels and chemicals, the production of construction materials does not require the presence of an external energy carrier and is based on a process called mineralisation (also referred to as mineral carbonation), i.e. the formation of stable carbonates from the reaction of CO_2 with calcium- and magnesium-oxide containing fractions. Carbonation is a naturally occurring phenomenon and can be accelerated under industrial conditions. The resulting product binds CO_2 permanently and may be used in the construction industry.

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Scientific evidence on CCU's potential

In the recent years, the CCU concept has attracted more attention not only as a way to reduce emissions but also as a way to replace fossil carbon feedstock. Because of their lack of granularity, Integrated Assessment Models (IAM's) used in scenario building exercises have yet failed in simulating the complexity of the different CCU options to realise net zero or negative CO_2 emissions (e.g. Detz and Zwaan, 2019). Consequently, no exhaustive quantification exists today on the climate mitigation potential of this large panel of technologies. Nevertheless, their key role is becoming increasingly recognised as one building block in a portfolio of mitigation measures (e.g. Grüber et al., 2018, IEAGHG, 2019, Sick, 2021). Indeed, CCU technologies have been estimated to be able to utilise up to 8 Gt of CO_2 per year by 2050 (Hepburn et al., 2019), this is equivalent to approximately 15% of current global CO_2 emissions. In parallel, more scientific information on the potential of CCU for climate mitigation from a life cycle perspective is becoming increasingly available as recent LCA studies indicate (examples below).

When CO_2 is captured directly from the air and stored permanently via **mineralisation** into building materials, CCU can also create negative emissions. In fact, CCU technologies for mineralisation could reduce climate impacts over the entire life cycle based on the current state-of-the-art and today's energy mix. Up to 1 Gt per year of the cement market could be substituted by mineralisation products. Additionally, mineralisation technologies support the development of a circular economy, e.g. when CO_2 is bound in industrial waste fractions like steel slags or ashes to create materials. (Ostovari et al., 2020; Di Maria et al., 2020; Hills et al., 2020; Zevenhoven, 2020; Huang et al., 2019).

Unlike other options, CCU technologies provide drop-in **fuel** solutions which can be implemented without requiring significant modification of existing infrastructure for production, distribution and use. Life-cycle analysis demonstrate that both point source and DAC to fuel pathways can provide climate benefit over conventional diesel fuel if a low carbon source of electricity is used. The estimated potential for the scale-up of CO_2 utilisation in e-fuels varies widely, from 1 to 4.2 Gt CO_2 yr^{-1}. (Sources: Ampelli et al., 2015; Daggash et al., 2018; CONCAWE, 2019; Liu et al., 2020; Hepburn et al., 2019; Farfan et al., 2019; Ram et al., 2020).

Another important asset of CCU technologies is the utilisation of CO_2 in the **chemical** industry as carbon feedstock to replace fossil resources and detach from a fossil carbon feedstock. Recent studies have shown that the majority of CCU-to)chemicals pathways show a comparative advantage in terms of LCA emissions against the fossil counterparts. Estimates show that this substitution could reduce annual GHG emissions by up to 3.5 Gt $CO_{2\text{-eq}}$ in 2030. (Kätelhön, et al., 2019; Thonemann and Pizzol, 2020; Artzt et al., 2018; Sternberg et al., 2017; Daggash et al., 2018; Thonemann, 2019).

When we are considering CCU products, the duration of the CO_2 storage into the product strongly varies from days to centuries according to the application. However, in term of environmental assessment, CCU technologies should not be assessed only with respect to the amounts of CO_2 that can be used nor to the duration of storage; it is rather essential to determine the life cycle of the CO_2-based product generated (e.g.

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Bruhn et al., 2016, Zimmerman et al., 2018, Nocito and DiBenedetto al., 2020). If these products are assumed to be substitutes for fossil-based products and thus provide the same service (i.e. it would be used and disposed of according to the same patterns as conventional products), the focus of the life-cycle-analysis may lie in the cradle-to-gate phase (e.g. Kätelhön, et al., 2019). Two important points should be highlighted in this respect (Arning et al., 2019, IEAGHG, 2019b, Zhu, 2019): (i) If CO_2-based products can be produced with a lower environmental impact (including GHG emissions) than fossil-based ones, an environmental benefit can be asserted, independent of the storage time of CO_2 in the products; (ii) If CO_2-based products are recycled i.e. if their end of life CO_2 emissions are captured to generate new products, the duration of CO_2 storage in a product is not anymore crucial to consider in the life cycle analysis.

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CCUS SET-Plan initial targets and technical progress

The CCUS Implementation Plan of the SET-Plan has introduced in 2017 a set of 8 R&I Activities to reach 10 Targets for the accelerated deployment of CCU and CCS technologies in Europe. The Implementation Working Group 9 (IWG9) is responsible to monitor the progress towards achieving those targets. R&I Activity 7 was dedicated to the development of CCU and corresponded to Targets 8 and 9. This chapter (i) briefly describes the original targets and the progress that has been achieved towards reaching them and (ii) describes the revised targets that correspond better to the more ambitious climate targets of the EU climate law that has come into force in July 2021.

Initial target 8

At least 3 new pilots on promising new technologies for the production of fuels, value added chemicals and/or other products from captured CO_2

Target 8 attempts to reflect in one aggregated target the development of different CCU value chains. It presents sub-targets, referred to as "deliverables" in the Implementation Plan, from the below thematic areas: *enable competitive CO_2 valorisation; carbonation of industrial wastes with CO_2; transformation of CO_2 and renewable energy into methanol; transformation of CO_2 and renewable energy into chemicals and fuels; production of polymers from CO_2; advanced solar chemicals and fuels from CO_2 – direct utilisation of solar energy for CO_2 valorisation*. All sub-targets are to be pursued under the lens of CO_2 emission reduction potential. Target 8 was very relevant in the Implementation Plan developed in 2017, as CCU technologies were at the time promising innovative technologies that needed validation at pilot scale (TRL 5-6). The consolidated target, although rendering reporting at aggregated level challenging, has been relevant as this ensured that each value chain would be developed in parallel so that CCU technologies could showcase their contribution for GHG emission reduction in different economic sectors and for different product markets (e.g. energy intensive industries, transport, chemical sector, etc.).

Technical progress

At an aggregated level, it is safe to say that targets for pilot installations by 2020 have been reached. Funding at EU and national level permitted to bring various CCU technologies (including capture) to the stage of pilot validation and often also beyond. Examples of such projects/installations are given below, showing that more than 3 pilots have been developed by 2020.

Project/Company	Product	CO_2 Source	Output	Location
MefCO_2, FReSMe	Methanol	Flue gas	1 t/d	Germany,Sweden
Kopernikus P2X	Fuel	DAC	10 l/d	Germany
Georg Olah Plant	Methanol	Geothermal	4 kt/y	Iceland
STORE&GO	Methane	Bioethanol	1400 m^3/d	Germany
Jupiter1000	Methane	Flue gas	25 m^3/h	France
ALIGN-CCUS	DME	Flue gas	50 kg/d	Germany

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Twence	Sodium bicarbonate	Flue gas	8 kt/y	Netherlands
Carbon8 Systems	Aggregates	Flue gas	100 t	Netherlands
Atmosfair	Jet fuel	DAC	160 l/d	Germany

At the level of the individual thematic areas, not all sub-targets have been reached with pilot scale installations but in all thematic areas, progress is tangible and on-going towards achieving pilot testing by 2022, as some indicative examples below show:

Enabling competitive CO_2 valorisation. As introduced in the Implementation Plan (IP) this sub-target would require a combination of different elements: novel and efficient capture systems, robust catalytic processes, mobile and modular systems for capture and conversion, better knowledge of the quality of CO_2 streams; progress has been clear in these elements:

- A series of ongoing or recently completed projects aimed at validating **capture systems** at least at pilot scale highlight the increased attention given in R&I of capture systems (membrane based, absorption-based, etc.): Jupiter100 (FR) and Méthycentre (FR) using membrane systems to capture CO_2 from flue gases and transform it to methane; MEMBER (Spain-biomass gasification, Portugal-CHP plant, Norway-steam reforming hydrogen plant), GENESIS (Switzerland-cement plant, Belgium-steel plant), MOF4AIR (Turkey-refinery plant, Norway-CHP Plant, France-WtE), CARMOF (Greece-cement plant) testing different membrane separation systems across demo sites in EU; Further EU projects demonstrating capture technologies from energy intensive industries like LEILAC, CEMCAP & CLEANKER (cement plant) or STEPWISE & Carbon2value (steel plant).
- A series of ongoing or recently completed projects are specifically looking at **catalyst development** for efficient catalytic conversion of captured CO_2, indicatively: eCOCO2 (EU) with hybrid catalyst development for direct reduction of CO_2 to jet fuel; CO2Fokus (EU) with catalyst development for direct CO_2 conversion into DME and validation at a petrochemical site in Turkey; COZMOS (EU) with nanocatalyst development to convert CO_2 to fuels and chemicals. But also, companies and platforms that are specialized in catalyst development for CO_2 conversion like: Econic Technologies (catalyst development for polyol production), Avantium and the VOLTA technology (catalyst development for electrochemical conversion), the VOLTACHEM innovation platform for the development of electrochemical conversion processes, Harald Topsoe's catalytic technology for CO_2 reduction, etc.
- Particular focus has been also given to the development of **modular systems** for capture and conversion to increase flexibility and adaptability to site locations, indicatively we mention examples of : Aker Solutions and Carbon Clean with containerised flue gas capture systems; Climeworks with modular DAC systems; Carbon8 Systems with containerised mineralisation systems; ICO2CHEM with Mobile unit for chemical production; Kopernikus P2X with four stage containerised fuel production; CRI with pilot methanol unit in the FReSMe and ALIGN CCUS projects.

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- The **quality of the CO_2 streams** is examined within the various individual CCU projects that are monitoring and testing the level of impurities that downstream conversion can tolerate; besides, testing platforms like the Technology Centre Mongstad offer a test bed for different capture systems.

Conversion of CO_2 from flue gases with renewable electricity to methanol. Methanol has been the focus of CCU projects due to the versatile spectrum of possible uses either directly as a fuel or chemical or as intermediate for further fuels and chemicals. Below indicative examples showcase that the CO_2 to methanol concept has progressed considerably the last years with a series of projects at different TRL scales:

- Lower TRL projects looking at innovative catalytic systems for methanol production like METHASOL, LAURELIN.
- Examples of projects having achieved or targeting demonstration at pilot scale: TAKE-OFF and Westküste100 with methanol as intermediate for jet fuel production; MefCO2 and FReSMe with demonstration of methanol as fuel at product rates of 1 t/d; C^3-Mobility (methanol as intermediate of gasoline-like fuel at levels of 15.400 l); Carbon2Chem (methanol from stell gases at 75 l/d); Powerfuel (synthetic hydrocarbons at scales of 200 l/d).
- Projects that have already demonstrated commercial operation (Georg Olah plant from CRI in Iceland with 4kt/y and Circlenergy) and further projects announced for industrial scale operation (see below).

Conversion of CO_2 and renewable electricity to other chemicals and fuels. Apart for methanol, further other fuels and chemicals have been researched at least at pilot scales in a series of EU and national projects, indicatively:

- Jupiter100 and Méthycentre for the production e-methane; C2Fuel and FlexDME for formic acid and DME, ICO2CHEM and the Mobile Synthesis Unit for wax production in Germany; BOF2UREA and INITIATE for the production of urea based on sorption enhanced water gas shift capture technology (to be validated at TRL 6-7 in Sweden); Rheticus II for the production of specialty chemicals from CO_2 in a test facility in Germany starting operation in 2020; RECODE for validation at TRL 6 electrochemical conversion of CO_2 into cement additives; BioReCO$_2$VER for the production of isobutene and lactate at pilot scale; OCEAN & CO2EXIDE aiming at demonstrating at TRL 6 the production of oxalic acid and ethylene oxide, respectively; PHECAM aiming at pilot scale production of formic acid;

Carbonation of industrial waste fractions with CO_2. Many industrial residues are an attractive input in the mineralisation process and can bind CO_2 in the form of carbonate. Projects like FastCarb in France (retrofitting industrial equipment at two cement plants for accelerated carbonation of recycled concrete aggregates aiming at TRL 7 validation), C^2inCO_2 (carbonation of recycled concrete) or the recently completed CO$_2$MIN in Germany have progressed the concept of mineralisation at pre-industrial scale. But also companies like Carbon8 Systems with its containerised accelerated carbonation technology treating directly flue gases for the production of aggregates (with pilot installation in France treating cement by-pass dust); Orbix and VITO

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with the Carbstone technology for the production of bricks from steel slags (with demonstration in a pavement in the city of Ghent).

Production of polymers from CO_2. Pilot validation has been accomplished also in this strand with projects like Carbon4PUR aiming to validate at TRL 6 the production of polyurethane or TRANSFORMATE to produce biopolymers from CO_2 via formic acid. Also, pioneer companies like Covestro (Germany), Econic Technologies (UK) are also commercially active in the CO_2-to-polymer strand.

Advanced solar chemicals and fuels from CO_2: Various research teams working on breakthrough solar fuels and chemicals directly from sunlight through photocatalytic technologies and some projects are leading the way for pilot validation in the near future: NEFERTITI, METHASOL, SUN2CHEM, SUN-to-X. Important role in the development of this strand will be played by the SUNERGY Initiative (merger of the former Flagship candidates SUNRISE and ENERGY-X) that supports and develops the solar fuels and chemicals community in Europe.

Initial target 9

Setup of 1 Important Project of Common European interest (IPCEI) for demonstration of different aspects of industrial CCU, possibly in the form of Industrial Symbiosis.

IPCEI is an instrument that allows Member States to support industrial actors in the development of large-scale transnational projects in ways that would otherwise not be possible due to State Aid regulation. IPCEI are based on the definition of Strategic Value Chains (SVC), i.e. chains of economic activities of systemic importance for the competitiveness of the EU and with significant potential for growth and job creation. Several SVC have been defined over the years and IPCEI have started to be developed in some of them (e.g. Microelectronics, Batteries). Two SVC of particular interest for CCU are the ones on “Hydrogen Technologies and Systems” and “Low CO_2-emission industries” and CCU projects can be part of the corresponding IPCEI. target 9 is very relevant for the goals of the CCUS SET-Plan because it is a way to promote on the one hand the active and concrete engagement of Member States in CCU deployment and on the other side the collaboration among European industrial players with common interests. It is a way to incentivize transnational collaboration for large scale, mature but not yet cost-competitive projects.

Technical progress

At the time of defining the CCUS SET-Plan targets, the intention was to incorporate CCU technologies in the SVC so that the corresponding IPCEI instrument would promote circular industrial systems and industrial symbiosis where emissions from one industry or sector could become input for another. The SVC defined in 2019 did not set forward a stand-alone SVC for CCU but they incorporated the concept of CCU in the two SVC mentioned above that represent larger value chains. Therefore we could say that the target 9 is partially achieved, although its original formulation would require adaptation.

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Initial focus and resources of Member States was concentrated on the earlier IPCEI on batteries and microelectronics, therefore the launch of the IPCEI on "Hydrogen technologies and systems" only started in 2020 with many Member States publishing calls for expression of interest towards the industrial actors in their territories. Currently, the process is at the stage where many Member States have identified projects of interest (see for example Germany, Denmark, Belgium) and they are coordinating among themselves to build on the element of integrated value chains with common structures and programmes and transnational collaboration. It is expected that the development of the "Low CO_2 emissions industries" IPCEI will follow the one on Hydrogen technologies & systems", while some Member States have published the expression of interest for both of them at the same time (see for example Austria).

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CCUS SET-PLAN

CCUS SET-Plan revised targets and justification

The ambitious EU's climate goals for 2030 and 2050 ask for more ambitious targets in terms of CCU technology deployment. Technical progress over the last years has clearly been beyond pilot validation and a series of support instruments have been acknowledging and including CCU into the scope. It is therefore timely and necessary to revise the CCUS SET-Plan targets regarding the CCU targets 8 and 9 accordingly.

Revised target 8

By 2030, several demonstration installations producing CO_2-based fuels, chemicals and materials at the scale of tens of kt/a and contributing to EU 2030 and 2050 climate and circularity objectives.

It has been shown in the progress of original targets that several pilots have been already established to prove technical viability of CO_2-based products. Demonstration at industrial environments at scales of several kt/a is within reach as also showcased by the examples below that are under preparation and ready to become operational in the next 4-5 years:

Project	Product	Country	Output (kt/a)	Operation
Greenlab	Methanol	Denmark	10	2022
LiquidWind	Methanol	Sweden	50	2025
C2PAT	Fuels	Austria	500	2030
North-CCU-Hub	Methanol	Belgium	44	2025
Port of Antwerp	Methanol	Belgium	8	2025
Westküste100	Jet fuel	Germany	20	2025
Norsk e-fuel	Jet fuel	Norway	8	2023
Mo Industrial E-fuel	Methanol	Sweden	800	2025
ProjectAir	Methanol	Sweden	200	2025
DOW Stade	Methanol	Germany	200	2025
Statkraft	Methanol	Norway	100	2023
Green Fuels for Denmark	Fuels	Denmark	160	2027
REIntegrate	Methanol	Denmark	10	2023
Zenid	Jet fuel	The Netherlands	8	2026
KerEAUzen	Jet fuel	France	8	2026
Synkero	Jet fuel	The Netherlands	50	2027
Columbus	e-methane	Belgium	17	2025
Lanjatech/SAS	Jet fuel	Sweden	50	2026
Nordic Electrofuel	Jet fuel	Norway	8	2023

Given that there is a variety of CCU processes and to accommodate potential differences of technical maturity, this target could be disaggregated into further sub-targets depending on the pathway (e.g. artificial

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photosynthesis systems follow in TRL and in product volumes the pathways to produce methanol). However at an aggregated level, it is safe to say that scales of several tens of kt/a within the next year is an ambitious but realistic target.

The revised target 8 reflects the technological development of CCU pathways, to ensure that the relevant technologies can be demonstrated at relevant environments before investment in commercial operation (production volume at commercial scale would be specific to the type of product). Investment in large-scale commercial plants will depend on various non-technical aspects (cost, regulation, market demand, infrastructures, competitive access to renewable electricity, etc.). The commercial character is reflected in the update of target 9.

Revised target 9

By 2030, first large-scale commercial CCU installations enabled by a supportive regulatory framework and risk-sharing financial measures at national and EU level including IPCEIs in the context of new industrial alliances mentioned in the New Industrial Strategy for Europe.

This target considers that, by 2030, following the progress in target 8, demonstration of CCU technologies at industrial scales will be achieved and the first commercial installations will be operational. It also addresses factors that are important for commercialization, which are not related to the technological dimension, i.e. policy framework and financing instruments. The update of the 2020 Industrial Strategy for Europe highlights the important role of the greentech sector in increasing EU's competitiveness and leading role in reaching climate goals. The industrial alliances developed therein (see example the Clean Hydrogen Alliance) are bringing together stakeholders along the value chain and consolidating their efforts for faster deployment and collaboration. The Fit-for-55 package lays down the major policy instruments that will guide the EU in achieving the ambitious climate goals and CCU is well represented (see also below). The IPCEI instrument remains instrumental for a large scale deployment of CCU technologies and for fostering international collaboration that will lead to faster commercialization. Further instruments will support this path like the Innovation Fund, the Recovery and Resilience Facility, the InvestEU Fund. So, this target is revised to accommodate the objective of achieving commercial uptake of CCU-products.

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Recommendations to achieve revised targets

While progress on the development of CCU technologies was evident the previous years, the transition to higher scale industrial concepts and the realisation of the revised CCUS SET-Plan for demonstration at industrial scale and first commercial plants will require further concentrated effort. The following section presents some recommendations on how to achieve these goals, basing on the work that has been conducted within the CCUS SET Plan, for example the exchanges in the IWG9 Plenary meetings, the sub-group "Utilisation" meetings and exchanges and desktop research.

The following recommendations are grouped under three basic categories: (i) R&D of technical and non-technical nature, (ii) Financing and (iii) Policy.

R&D for technical and non-technical elements

Further development of capture systems. The IEA recognises carbon capture as indispensable technology to reach climate neutrality by 2050. Whether utilised or stored, CO_2 needs to be annually captured at Gt scale, therefore considerable resources need to be dedicated to the scale-up of capture systems to match different CO_2 streams from different sources: industrial and atmospheric. This will require the continuous development of capture processes (absorption, adsorption, membrane separation, etc.) with novel materials (e.g. solvents, metal-organic frameworks, etc.) that will be cost-efficient, durable and easily regenerated.

Novel catalysts for catalytic conversion. A considerable part of CCU technologies entail the use of catalysts for the efficient conversion (electrochemical, photochemical, thermochemical) of CO_2 into an array of products. Therefore, catalysis plays a crucial role in the development of the CCU concept. Current progress on the production and deployment of homogeneous and heterogeneous catalysts at industrial scale is not yet fast enough to cover projected needs of CCU product deployment. The design of such catalysts should be based on robust, cost-effective and abundant raw materials to achieve improved functionalities and high conversion efficiencies.

Integrated capture and conversion. The majority of industrial systems for capture and conversion of CO_2 are based in separated, two-reactor processes that would allow better control and monitoring of the process. However, integrated systems with in-situ capture and conversion are a promising R&D pathway to increase conversion efficiencies and reduction of CAPEX costs. Process intensification with such bi-functional catalysts is currently studied not only for combining capture and conversion into a single reactor[1], but also for merging two-step conversion processes into one (e.g. CO_2 to olefins into a single reactor without intermediate methanol production[2]).

[1] See Omodolor et al., 2020, Ind. Eng. Chem. Res. 2020, 59, 40, 17612–17631, https://doi.org/10.1021/acs.iecr.0c02218; Kim et al., 2018, ACS Catal. 2018, 8, 4, 2815–2823, https://doi.org/10.1021/acscatal.7b03063; Hu et al., 2021, Appl. Catal. B, 284, 119734, https://doi.org/10.1016/j.apcatb.2020.119734
[2] See for example project TAKE-OFF

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Optimised CO_2 uptake rate. For process not involving the transformation of the CO_2 molecules but its chemical incorporation of the molecule (e.g. in mineralisation) it is important to optimise the process conditions so that more CO_2 on a per weight basis (higher than 15%) can be bound into the final product. Industrial residual fractions like steel slags, cement dusts, incineration ashes, construction and demolistion waste are typical waste fractions considered for mineralisation and further efforts should be dedicated to analysing their suitability. Such fractions are typically found in large quantities and limit the implementation of CCU technologies only on-site because the logistical burden of treating them off-site (e.g. transport) is considerable when the CO_2 uptake rate is not sufficient.

Metrology for CCU processes. Depending on the final CCU application and the final product, different levels of CO_2 purity will be required. Catalytic processes will need purer streams of CO_2 to protect the applied catalysts and would therefore not tolerate high concentrations of impurities; Mineralisation on the other side would not require high purity CO_2 streams. It is important to have metrology protocols and analytical methodologies in place for accurate measurements of the CO_2 quality at high flow rates, similar to the ones of industrial processes. It is also important to be able to examine how CO_2 quality requirement might influence transport infrastructure and to monitor and verify for accounting purposes the CO_2 uptake and duration of binding in the different CCU products.

CCU in modelling and scenario building. Integrate Assessment Models lack the granularity that is necessary to include complex processes like CCU. As a result, CCU has been generally underrepresented in energy and industrial system modelling studies and a systematic and comprehensive quantification of the CCU potential in scenario development for climate change mitigation has been missing. Further effort should be made in including CCU in modelling activities and scenario building so that future projections can be as inclusive and accurate as possible on solutions to reach climate neutrality.

Sustainability Assessment and public acceptability. It is essential that CCU technologies and projects at industrial scale conduct Life Cycle Assessments (LCA) and Techno-Economic Assessments (TEA) to showcase the viability and environmental integrity. The previous years have been marked by an increasing number of LCA studies providing scientific information (as discussed above) about the environmental benefit of CCU products compared to fossil-based conventional alternatives. It is essential that this is continued in a systematic way. Efforts have been concentrated on harmonising LCA and TEA approaches for CCU and resources are now available and need to be used for consistent implementation[3]. At the same time more studies on social acceptability, social benefits (like job creation), public engagement and perceptions in the public media sphere[4] are required, so that there is clear and evidence-based information to the public on what CCU exactly is, what its potential for climate mitigation is and what the limitations are.

[3] https://assessccus.globalco2initiative.org/

[4] See for example https://co2-utilization.net/fileadmin/user_upload/CO2WIN_Medienanalyse_2021.pdf (in german)

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Policy

A supportive policy and regulatory framework is one of the most impactful tools towards the adoption and deployment of innovative technologies, also in the case of CCU. The reason for that is that such a framework gives a positive signal to industrial actors and investors that the technology is recognised and the CCU product will find a market and reach cost-competitiveness with conventional fossil-based alternatives.

With the publication of the fit-for-55 package in July 2021[5], the European Commission has suggested a series of legislative instruments to implement the EU Green Deal and lead the way towards achieving 2030 climate goals. Revision of existing instruments like the Emissions Trading Scheme (ETS), the Renewable Energy Directive (REDII), the Energy Taxation Directive (ETD) or the introduction of new instruments like ReFuel EU for Aviation, Fuel EU Maritime, the Carbon Border Adjustment Mechanism (CBAM) are mostly interconnected and will, some more than the others, influence the deployment of CCU technologies. Some new positive elements already appear in the proposal of the Commission and **it is crucial that these elements are maintained in the final form of the legislative packages** after the negotiations with the EU Parliament and the Council:

- Recognition that CO_2 permanently and chemically bound in products and not released into the atmosphere under normal use removes the obligation to surrender ETS allowances (under the Revision of the ETS); *important is however that the definitions of permanent binding and normal use are clear and inclusive.*
- Recognition that the use of RFNBO[6] renewable fuels of non-biological origin (RFNBO, among them also CCU fuels) produced from captured CO_2 should not lead to a double counting of the emissions finally released by their use (under the Revision of the ETS); *important is however that the announced delegated acts laying down the rules for the avoidance of this double counting are developed as soon as possible.*
- Covering at least 2.6% of the energy supplied in the transport sector by RFNBO and extension of the use of renewable CCU fuels to further industrial sectors by suggesting that 50% of the hydrogen use in industry to be covered by RFNBO (under the revision of REDII).
- Introduction of specific shares of renewable CCU fuels in aviation (under ReFuel EU) and recognition of the role of those fuels in the maritime sector (under Fuel EU maritime).
- Zero taxation rates for 10 years for renewable CCU fuels in certain types of air and waterborne navigation (under revised ETD).

[5] https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3541
[6] Renewable fuels of non-biological origin, typical examples being renewable hydrogen and CCU fuels based on renewable electricity

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- The introduction of carbon contracts for difference as a support scheme for innovative technologies with a potential for emission reduction (under the revision of ETS).

In addition to the fit-for-55, **it is important to implement the action plan on** sustainable carbon cycles that the Commission recently published. This communication acknowledges for the first time the role that CCU can, on its own merit, play in establishing sustainable industrial carbon cycles and also sets the framework for definition and certification of carbon removals. It is therefore important that the framework develops swiftly clear guidelines and robust methodologies to allow reuse and removal of carbon.

Despite these positive elements there are still important steps to take to provide a holistically and consistently supportive framework for the adoption and accelerated deployment of CCU technologies:

- In June 2020, the Commission published the **EU Taxonomy for sustainable finance**[7], an instrument that would define which economic activities are considered sustainable and therefore have easier access to financing. The Taxonomy Regulation[8] establishes 6 environmental objectives (climate change mitigation; climate change adaptation; the sustainable use and protection of water and marine resources; the transition to a circular economy; pollution prevention and control; the protection and restoration of biodiversity and ecosystems). The Commission will propose, through Delegated Regulations, lists of economic activities and associated technical screening criteria determining how each activity contributes to the environmental objectives. The first Delegated Regulation on climate change mitigation and adaptation was published in June 2021[9]. The second Delegated Act on the remaining objectives is currently under preparation[10].
  - Despite the recognition of CCU under Article 10 of The Taxonomy Regulation[11], the Delegated Act on climate change only partially acknowledges fragments of CCU processes[12]. The use of captured carbon as a whole is referred to a further review taking place in three years.
  - **It is of paramount importance that CCU is entirely included in both Delegated Regulations for climate change mitigation and the transition to a circular economy**. Further delay of CCU inclusion might hamper access to financing which will be detrimental in achieving accelerated deployment of industrial installations.
- The upcoming Delegated Act on Art. 27(3) of the Renewable Energy Directive (RED II) defines the rules to produce hydrogen and other RFNBO from renewable electricity. It is the most important lever for a successful market ramp-up of RFNBO in this decade since it concerns the use of RFNBO in both

[7] https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/eu-taxonomy-sustainable-activities_en
[8] Regulation (EU) 2020/852
[9] C(2021) 2800
[10] See https://ec.europa.eu/info/publications/210803-sustainable-finance-platform-technical-screening-criteria-taxonomy-report_en
[11] Regulation (EU) 2020/852, Article 10: "An economic activity shall qualify as contributing substantially to climate change mitigation […] by: […] (e) increasing the use of environmentally safe carbon capture and utilisation (CCU) […] technologies that deliver a net reduction in greenhouse gas emissions;"
[12] C(2021) 2800, Annex I: activity 3.10 - Manufacture of hydrogen (and hydrogen-based synthetic fuels); activity 3.6 - Manufacture of other low carbon technologies; activity 9.2 - Research, development and innovation for direct air capture of CO_2

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transport and industry. **Acknowledging that additional renewable electricity capacities are required, it is important that this delegated act is considering industrial realities and not imposing unrealistic conditions** to only some electricity consumers for accessing this renewable electricity. Additionality is most effectively addressed at a market-driven system level and could be part of national regulation. This is acknowledged in the fit-for-55 proposal for REDII revision, which is inviting Member States to create a framework for deployment of additional renewable energy capacities based on the market demand also for RFNBO, among other uses.

- It is also urgently **important to present the Delegated act on the methodologies for determining GHG savings from RFNBO** and RCF (recycled carbon fuels) from Art. 28(5) of the REDII because this delay increases the uncertainty behind on-going and up-coming projects.

For a wider political acknowledgment, **CCU should be better incorporated in the National Energy and Climate Plans that set strategic priorities at national level**. An early assessment shows that not many countries have included CCU elements in their plans and those who have do so with little detail on concrete measure for deployment. This is also closely linked to other national plans like the Recovery and Resilience plans (see next section on funding).

Finally, the **CCUS Forum** established under the Energy System Integration Strategy is expected to play an important role in designing a European Strategy for CCS and CCU. The Forum convened for the first time in October 2021 and it is important that it establishes itself as **a platform that is regularly monitoring CCS and CCU implementation in a balanced way** and gathering the knowledge of relevant stakeholders.

Funding

Similar to all innovative greentech technologies, CCU also requires a considerable funding effort to bring these technologies to commercialization. CCU will require the **creation of a funding ecosystem** that will include public funding actors that can de-risk an investment, private funding actors that can leverage more market-oriented capital and industrial/corporate actors that can help scaling up a technology at industrial scales. It is important that these actors coexist because accessing the one or the other type might be more difficult depending on the maturity of the technology. Furthermore, a private actor can commit to a project more easily if public funding is also secured and vice-versa; it is therefore important that all these actors are properly educated on the opportunities that CCU can offer so that they can include it in their portfolios.

When considering **public funding it is important that it remains consistent along the entire TRL scale**. Technological innovation requires time and funds to ascend the TRL levels and it is essential that there is no interruption in funding for projects that are successfully advancing. This would mean that a CCU project that is funded under a Horizon Europe topic at year X and brings the technology to TRL 5 after 4 years, should be able to find a corresponding topic in the Work Programmes that will be defined 4-5 years later. Accordingly,

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when the project has successfully reached the TRL level that is fundable under Horizon Europe, it should be able to profit from an instrument that will allow it to reach pre-commercial maturity (e.g. Innovation Fund).

The Innovation Fund is one of the largest funding instruments for demonstration of low-carbon technologies. It will considerably help small-scale and large-scale projects reach commercial maturity and contribute to Europe's climate goals for 55% emission reductions by 2030. The first calls of the Innovation Fund close with 30 small-scale projects (out of 232 applications requesting more than 1 B€) and 7 large-scale projects (out of 311 applications requesting more than 21.7 B€) being funded for a total funding of 100 M€ and 1.1 B€, respectively. Considering the high oversubscription rate of the first call (10x for small-scale and 20x for large-scale) and considering that the Innovation fund requests that funded projects reach financial close within 4 years, if we want to see real contribution to EU's climate goals by IF projects within the decade, a **considerable front loading of the Innovation Fund should take place by 2025**. The second large-scale call is doubling by 50% its budget, also led by the higher CO_2 prices. This increase must be more pronounced at least for the next three calls to be able to fund a considerably higher number of projects.

As mentioned above, the IPCEI instrument is essential for the large scale deployment of technologies that can have a transnational impact. Apart from the one on "Hydrogen Technologies" that is on-going, **Member States should dedicate resources in the launching of the IPCEI on "Low CO_2-emission industries"**, which is by default a value chain that is relevant for the entire Europe. It is expected that this new IPCEI will address CCU projects directly as CCU technologies are a very relevant solution to reduce emissions in industry.

Apart from the IPCEI instrument, it is important that Member States dedicate more effort in synchronizing national and EU priorities and complementing EU and national funds for green technologies. An important example is the Recovery and Resilience Facility, that is based on the **Recovery and Resilience Plans** of each Member State allocating minimum 37% of expenditures for climate investments and reforms. Some countries have included CCU in their plans (see Germany, Denmark, Finland, Belgium) and it is important that further countries follow this example as this is a good opportunity for CCU to be included in national strategies for greener economies and receive funding for implementation (see e.g. calls for funding in Germany, the Netherlands, UK).

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