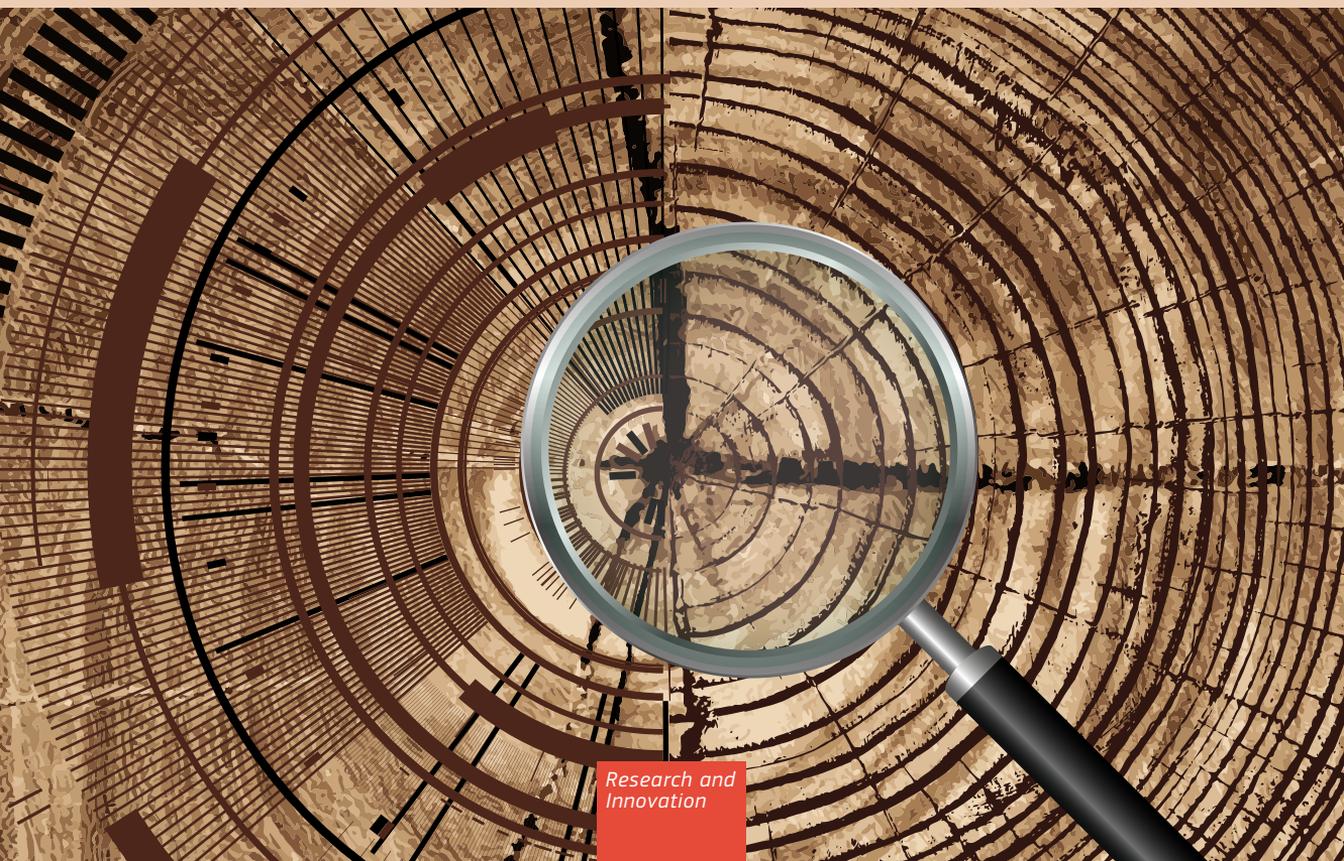




*Scientific Advice
Mechanism (SAM)*

Novel
**carbon capture
and utilisation**
technologies

*Group of Chief Scientific Advisors
Scientific Opinion 4/2018*



*Research and
Innovation*

Novel carbon capture and utilisation technologies

Group of Chief Scientific Advisors

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Directorate-General for Research and Innovation
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EUROPEAN COMMISSION

Scientific Advice Mechanism (SAM)
INDEPENDENT SCIENTIFIC ADVICE FOR POLICY MAKING

Novel carbon capture and utilisation technologies

Group of Chief Scientific Advisors
Scientific Opinion 4/2018
(Supported by SAPEA Evidence Review Report No 3)

Brussels, 23 May 2018

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This Scientific Opinion (hereafter the Opinion) was delivered by the Group of Chief Scientific Advisors (hereafter the Group) to the European Commissioner for Research, Science and Innovation, Carlos Moedas on 23 May 2018. It responds to a request from the European Commission which the Group accepted on 28 July 2017. The members of the Group of Chief Scientific Advisors in charge of developing this Opinion were Elvira Fortunato (Rapporteur) and Rolf-Dieter Heuer (Chair). The Opinion has been endorsed by all the members of Group.

The Group of Chief Scientific Advisors wishes to thank the many contributors for their support and input in the preparation of this Scientific Opinion:

- The Science Advice for Policy by European Academies consortium (SAPEA)¹ - a key component of the Scientific Advice Mechanism. Euro- CASE, represented by Yves Caristan, assumed responsibility on behalf of SAPEA for an Evidence Review Report on the subject. This was prepared under the leadership of SAPEA Working Group Chair Robert Schlögl (Max Planck, Germany) and vice-chair Marco Mazzotti (ETH, Switzerland), aided by a SAPEA staff team led by Wolf Gehrisch (Euro-CASE).
- All the scientific experts and stakeholders from the science, policy, industry and civil society communities who contributed to the SAPEA report, expert workshop, stakeholder meeting and other ad hoc meetings and consultations – the full list can be found in Annex 1.
- The European Commission's DG Joint Research Centre, DG Climate Action, DG Research and Innovation and DG Internal Market, Industry, Entrepreneurship and SMEs.
- The European Commission's SAM Unit support team (Maria da Graça Carvalho, Dulce Boavida, Jacques Verraes and Maurizio Salvi).

¹ SAPEA brings together knowledge and expertise from over 100 academies and learned societies in over 40 countries across Europe. Funded through the EU's Horizon 2020 programme under grant agreement No 737432, the SAPEA consortium comprises Academia Europaea (AE), All European Academies (ALLEA), the European Academies Science Advisory Council (EASAC), the European Council of Academies of Applied Sciences, Technologies and Engineering (Euro-CASE) and the Federation of European Academies of Medicine (FEAM)

EXECUTIVE SUMMARY

The European Union has committed to achieve an economy-wide domestic target of at least 40% greenhouse gas (GHG) emission reductions for 2030 and at least 80% GHG reductions by 2050. This should allow the EU to contribute to keep global warming well below 2°C as agreed by the almost 200 signatory parties to the 2015 Paris Climate Agreement.

Achieving those reduction targets requires the deployment of new and efficient technologies, appropriate legislative and policy initiatives, as well as investments in research and innovation ('R&I') and an appropriate financial framework to facilitate the demonstration and deployment of technologies in the higher range of TRLs (Technology Readiness Level). Among the techniques that can mitigate CO₂ emissions are those that are referred to as Carbon Capture and Utilisation that included capture, conversion and hydrogen generating technologies.

The Group of Chief Scientific Advisors was asked by the European Commission to advise on the climate mitigation potential of Carbon Capture and Utilisation (CCU) technologies in view of future policy decisions in this field, including on financial support by the European Union. The decisions should support technologies that are environmentally sound and provide genuine climate benefits.

The main questions put to the Group of Chief Scientific Advisors were:

- *Under what circumstances Carbon Capture and Utilisation for production of fuels, chemicals and materials can deliver climate benefits and what are their total climate mitigation potential in the mid- and long-run?*
- *How can the climate mitigation potential of CO₂ incorporated in products such as fuels, chemicals and materials be accounted for considering that the CO₂ will remain bound for different periods of time and then may be released in the atmosphere?*

This Scientific Opinion provides evidence-based answers drawn from a literature review, a scientific expert workshop and stakeholder consultation. Its conclusions can be divided into the following five sections.

The Opinion concludes that:

- CCU may play a role to de-fossilise the economy and help reaching climate change mitigation targets;
- It can contribute to leaving fossil carbon in the ground, and closing the carbon loop above the ground;
- CCU can also accomplish a number of other services to society with a more efficient use of energy;
- The uptake of CCU will depend on the availability of abundant low-carbon energy and a favourable legislative and investment environment;
- The introduction of CCU could start with high-density CO₂ streams from industrial processes and progressively move towards capturing CO₂ from less dense sources.

The Opinion makes a set of recommendations that are summarised here:

Recommendation 1

To develop a methodology to calculate the Climate Mitigation Potential of CCU

It is strongly recommended that European Commission develops a rigorous cross-sectorial and systemic methodology to calculate the CO₂ Climate Mitigation Potential of CCU projects.

This will constitute a powerful set of European guidelines and standards for the analysis of CCU projects.

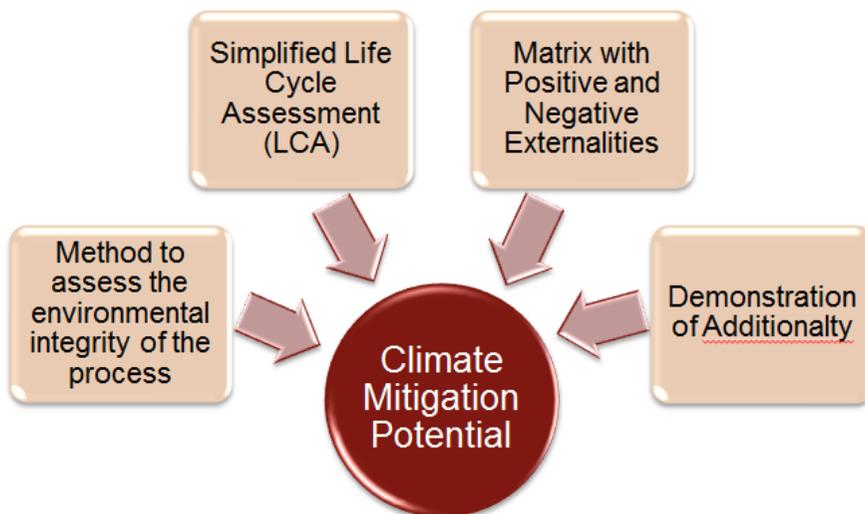


Figure 1 – Methodology to calculate the Climate Mitigation Potential of CCU (SAM secretariat)

Recommendation 2

Eligibility criteria for CCU projects

A CCU project should be considered eligible for funding or to be further included in Climate Change Schemes if the four following conditions are fulfilled:

- The required energy has low-carbon origin, with high availability and low cost
- Other, simpler and more cost effective solutions do not yield comparable products available in sufficient quantities
- The readiness level of CCU projects will meet the objectives
- There are supplementary benefits of the CCU projects in addition to climate mitigation potential.

Recommendation 3

CCU Novel Technologies

CCU technologies are not stand-alone but part of a system. Both TRLs (Technology Readiness Levels) and IRLs (Integration Readiness Levels) should be considered to assess the readiness of and the contribution that CCU technologies can make.

Recommendation 4

Regulatory and investment framework

It is strongly recommended that European Commission develops a cross-sectorial and systemic regulatory and investment framework for CCU applications comprising a set of clear rules and operational guidelines for CCU applications.

Recommendation 5

International framework - Party to the Convention on Climate Change

It is recommended that the European Commission advocates the methodologies of the Convention on Climate Change, the Kyoto Protocol and the Paris Agreement in international arenas, in particular in the scope of the UNFCCC².

² United Nations Framework Convention on Climate Change <https://unfccc.int/>



Introduction

1. INTRODUCTION

The CCU technologies that are examined in this Opinion cover the family of technologies that, combined in a system, convert otherwise industrially emitted or airborne CO₂ into fuels, chemicals and materials. These technologies encompass CO₂ capture and conversion technologies, as well as those for hydrogen production with which the carbon-atom from the CO₂ reacts chemically. The technologies are assessed on their ability to contribute to the implementation of the Paris Climate Agreement. Under circumstances to be clarified by this Opinion, CCU in principle offers the possibility of economically utilising CO₂ emissions with the perspective of closing the carbon cycle above the ground and differs fundamentally from CO₂ Capture and Storage (CCS) technology that aspires for permanent underground storage of CO₂.

This Opinion looks at novel technologies that can produce the abovementioned added-value products with ever-increasing efficiency by using renewable energy sources. These technologies use CO₂ as a raw material (feedstock) and integrate its carbon content in products for a shorter or longer period, i.e. until the product reaches its end-of-life and the carbon is released to the atmosphere or recaptured. The ability to remove CO₂ from the air and use it to replace fossil carbon as feedstock or fuel makes CCU potentially interesting for reducing our carbon footprint and for reaching climate change mitigation targets. CCU could thus drive industrial innovation and make energy-intensive industries competitive without sacrificing climate goals which the European Union is committed to reach.

The uptake of CCU faces technical and economic challenges that encourage and motivates scientific progress and research. But what remains unclear is the precise nature and the size of the climate benefits that can result from large-scale deployment of CCU. These depend on heterogeneous factors such as the kind of technology used, the type of conversion product manufactured, the source and nature of the energy needed to power such conversion, the source of the CO₂ feedstock, and the location and characteristics of the CCU installation.

A thorough scientific and technical assessment of the climate mitigation benefits and the economic potential of CCU are necessary to inform policies and funding decisions and to safeguard that support will be given to projects and technologies that provide real climate and environmental benefits over the whole life cycle of products.

Representatives of 195 nations and the European Union adopted the Paris Climate Agreement on 12 December 2015 at the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC)³. The Agreement deals with GHG emissions mitigation, adaptation and finance starting in the year 2020. All 197 UNFCCC members have either signed or acceded to the

³ <http://www.un.org/sustainabledevelopment/cop21/>

Paris Agreement that entered into effect on 4 November 2016. The Agreement aims to respond to the global climate change threat by keeping a global temperature rise this century well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C (see Figure 2).

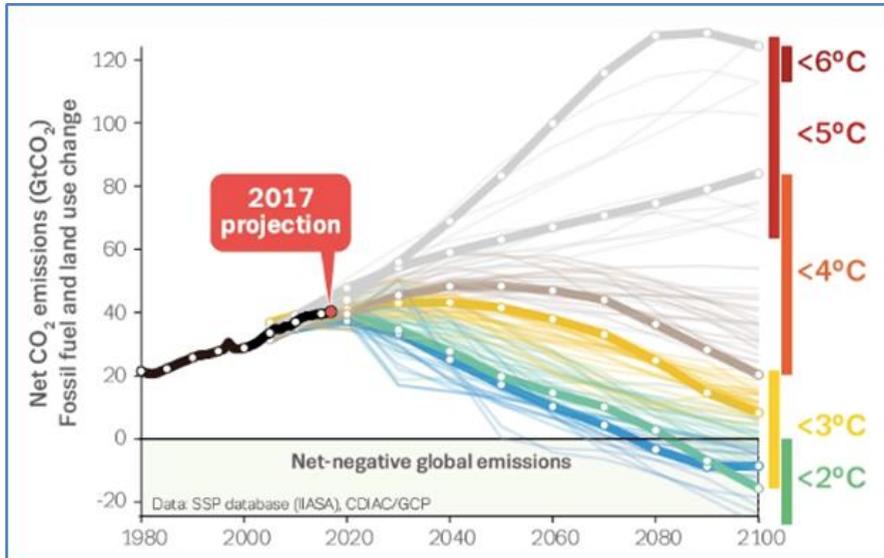


Figure 2 - Global CO₂ emissions since 1980 (solid black) compared to a high emissions scenario (red/orange) and a scenario compatible with limiting warming to 2 °C above pre-industrial levels (green). Source: Global Carbon Budget, 2017⁴.

In the above Agreement, the European Union has committed to an economy-wide domestic target of at least 40% GHG emission reduction for 2030 compared to 1990 (see Figure 3). By 2050, the EU aims to reduce its emissions by 80-95% compared to 1990 levels.

⁴ http://www.globalcarbonproject.org/carbonbudget/17/files/GCP_CarbonBudget_2017.pdf

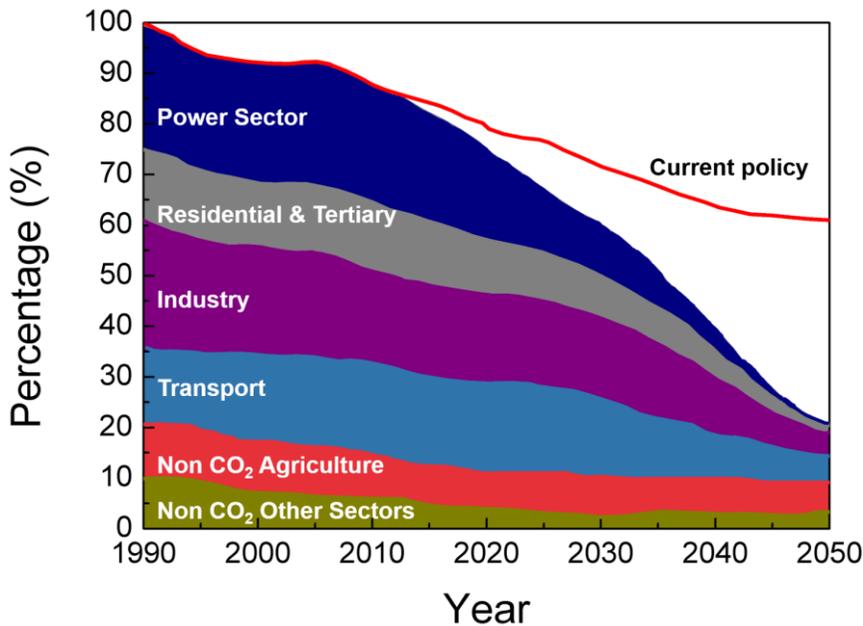


Figure 3 - Emission reduction pathways towards an 80% domestic reduction by 2050 ^{5,6}

The EU 2030 energy and climate framework sets three key targets for 2030 (40% cuts in GHG emissions, 27% share for renewable energy, and 27% improvement in energy efficiency) to meet the obligations of the Climate Agreement and that are further articulated in proposals that revise aspects of the current regulatory framework. Among these are amendments to the EU Emissions Trading System (EU ETS), and to the Effort Sharing Decision that sets GHG targets outside the sectors covered by the ETS that have to be reached by Member States. The 2016 *Clean Energy for All Europeans* package contains additional legislative measures to facilitate the clean energy transition, for instance the revision of the Renewable Energy Directive and the Energy Efficiency Directive.

These proposals are being negotiated by the co-legislators, the European Parliament and the Council, in view of being ready for implementation when the current 2020 climate and energy package expires.

The main objective of the present Opinion is to analyse the climate mitigation potential the CCU technologies for production of fuels, chemicals and materials in the mid- and long term. The Opinion has six chapters. Chapter 1, the present one, gives an introduction to the document.

Chapter 2 introduces the aim and scope of this Opinion and the questions that it addresses.

⁵ https://ec.europa.eu/clima/policies/strategies/2030_en;

⁶ https://ec.europa.eu/clima/policies/strategies/2050_en

Chapter 3 provides details about the methodology that was used for the drafting of this Opinion.

The evolution of the policy and legal context is the subject of Chapter 4. It describes the role of CCU in the framework of the instruments which the EU adopted to meet its international climate change mitigation commitments.

An overview of the main scientific knowledge is presented in Chapter 5. It draws on the evidence review report that was drawn up by SAPEA as well as workshop discussions and ad-hoc consultations with experts and stakeholders on the potential climate benefits of CCU.

In the final chapter 6, the Group of Chief Scientific Advisors formulates five recommendations for the Commission, such as the need to develop a methodology to calculate the climate mitigation potential of CCU that should not just inform EU but international policy- and decision-making; conditions for the funding CCU research and innovation projects, and the development of a regulatory and investment framework for CCU.



Aim and scope

2. AIM AND SCOPE

2.1. Aim

The Group of Chief Scientific Advisors was asked to provide scientific advice on the climate mitigation potential of CCU technologies, in particular CCU technologies that are environmentally safe and that may offer substantial climate benefits. The Group accepted the request (formally recorded in a 'scoping paper' – see Annex 2) and decided that, in order to issue an exhaustive scientific Opinion, it would also consider input from relevant interested parties.

2.2. Scope

CCU technologies offer a number of opportunities for European industry and the pursuit of European Union policy objectives, including:

- Supporting climate change objectives, by replacing crude oil and gas in chemicals and fuels but also through fixation of the CO₂ in materials;
- Supporting the circular economy, by converting waste CO₂ to products, industrial innovation and competitiveness, particularly important for energy-intensive industries, developing new and more efficient processes and creating new market opportunities;
- Supporting energy security and renewable energy deployment, through utilising excess renewable electricity and providing energy storage alternatives;
- Supporting the evolution of CO₂ capture systems, which may help deployment of Carbon Capture and Storage (CCS) technology, which in turn provides permanent and large-scale storage of CO₂.

CCU technologies are however at different stages of technological readiness, from laboratory testing to commercial demonstration and still face a number of technical challenges: advancement of knowledge is essential to improve the economic and environmental feasibility and the potential of the technologies. This includes for instance research in: the collection and purification of CO₂ from a variety of sources; the synthesis of "green" hydrogen via water splitting powered by renewable energy sources (RES) and CO₂ catalytic technologies.

EU international climate obligations require detailed monitoring and reporting of GHG. Currently, the EU Emissions Trading Scheme only provides derogation from accounting for the greenhouse gas emissions for CCS involving geological storage of CO₂, which is considered permanent in accordance with the CO₂ geological storage Directive⁷. CCU technologies bind the CO₂ molecule in a multitude of

⁷<http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0031&from=EN>

different products for different periods of time. Currently, unless captured CO₂ is permanently stored, it is recorded as an emission under the Emissions Trading Scheme Directive, due to the lack of a methodology for accounting for possible CO₂ releases in the future. The absence of such an approach reflects the novelty of the technologies as well as the multitude of different products and end-of-life possibilities. The economic feasibility of CCU technologies also depends on a number of factors, such as the costs of inputs (CO₂, electricity, catalysts, etc.), technological improvements and the price of products they substitute. CCU technologies like many innovations offer alternative processes and pathways to produce substitute products in the market, and therefore face commercial challenges in replacing long-established market incumbents. CCU technologies can provide storage of intermittent renewable energy but the need for such storage is in competition with other storage and grid management solutions and therefore potential in the future is unclear.

In this context, the Group of Chief Scientific Advisors was asked to provide scientific advice based on existing research on the climate mitigation potential of CCU technologies to inform future policy decisions in this field over the next couple of years, including financial support. In particular, the Group was asked to verify whether CCU would be environmentally safe and provide substantial climate benefits.

The review of the scientific evidence is summarised in a number of statements and policy recommendations, drawing on the best available scientific and technical evidence, knowledge and expertise in the area.



Methodology

3. METHODOLOGY

Following the modalities of the European Commission's Scientific Advice Mechanism (SAM), launched on 13 May 2015 ([IP/15/4970](#)), the Group of Chief Scientific Advisors requested the production of an Evidence Review Report by the SAPEA (Scientific Advice for Policy by European Academies) consortium.

The Chair of the SAPEA expert group was Robert Schlögl; the deputy chair was Marco Mazzotti. Additionally to the Evidence Review Report prepared by the above SAPEA expert group, on 25 January 2018 an expert meeting took place in Brussels (organised by the Group and SAPEA). The expert meeting was chaired by Elvira Fortunato and co-chaired by SAPEA. The Chair of the Group - Rolf-Dieter Heuer also attended this workshop. The workshop involved the experts who have worked in the SAPEA evidence gathering and literature review as well as around 25 additional experts identified by SAPEA. Representatives of Commission DG (RTD, CLIMA, ENER, ENV, GROW, JRC, MOVE) were invited as observers. The meeting provided the opportunity to share the experts' views on the SAPEA Evidence Review Report. Discussed elements included the use of renewable energy, cost of replacing significant portions of the present energy infrastructure, the share of biomass, hydro, nuclear, etc. in the future energy system as well as the full CCU cycle system.

In addition, in order to promote inclusiveness and transparency the SAM Secretariat organised a stakeholder workshop to allow relevant interested parties to voice their remarks, statements, concerns and expectations prior the adoption of the Group's Opinion. The stakeholder meeting was chaired by Elvira Fortunato.

The Group of Chief Scientific Advisors drafted the Opinion on the basis of the literature review, the assessment of the scientific evidence and the information gathered from interactions with scientists and stakeholders.

*Policy and Legal
Context*

4. POLICY AND LEGAL CONTEXT

4.1. EU Policy and Legislation

The European Council of October 2014 committed the EU to an economy-wide domestic target of at least 40% GHG emission reductions for 2030, which is in line with a cost-efficient pathway to at least 80% domestic GHG reductions by 2050⁸. This should allow the EU to do its share to keep global warming well below 2°C in line with the 2015 Paris Climate Agreement⁹. As negotiations on essential parts of the legislation are ongoing at the time of writing, the emissions reduction target or the part of the EU post-2020 budget that will be committed to climate-relevant spending are not yet known.

Achieving the reduction targets requires a wide range of legislative and policy initiatives, as well as investments in research and innovation ('R&I') to support the development and implementation of clean technologies.

CCU is a research priority under the Energy Union to allow the industrial and power sectors to reach climate objectives in a cost-effective way¹⁰. Stepping up R&I activities on the commercial viability of CCU is priority Action 9 of the Strategic Energy Technology (SET) Plan¹¹. Since COP21, the EU has been an active member in the global initiative of 22 countries known as Mission Innovation¹², which aims at doubling clean energy R&D investment by 2020 compared to 2013-2015 levels. In Mission Innovation, as well as via the SET-Plan, the EU is part of the Clean Energy R&D Focus Area on CCU and CCS¹³. A total of 61 projects on CCU technologies were funded from 2008 until 2018 under FP7 and Horizon 2020 for a total of 243M€¹⁴. A prize is funded under Horizon 2020 ("Horizon prize CO₂ reuse") to reward innovative products utilising CO₂ that could significantly reduce the atmospheric emissions of CO₂ when deployed at a commercial scale¹⁵.

The novel CCU technologies examined in this Opinion are assessed against their capability to attain the 2030 targets and 2050 objectives, and that are significantly more ambitious than the 2020 ones. These more ambitious goals are being transposed by the aforementioned amendments of Directives that regulate the energy and transport sectors: the Emission Trading Scheme Directive ('ETS') (2003/87/EC), the Renewable Energy Directive ('RED') (2009/28/EC) and the Energy Efficiency Directive ('EED') (2012/27/EU).

⁸ COM(2011) 112 final: A roadmap for moving to a competitive low carbon economy in 2050

⁹ https://ec.europa.eu/clima/policies/strategies/2050_en

¹⁰ <http://eur-lex.europa.eu/legal-content/En/TXT/?uri=CELEX:52015DC0080>

¹¹ https://setis.ec.europa.eu/system/files/Communication_SET-Plan_15_Sept_2015.pdf

¹² <http://mission-innovation.net/>

¹³ <http://mission-innovation.net/participating-countries/european-union/>

¹⁴ https://ec.europa.eu/info/sites/info/files/sustainable_p4p-report_2017.pdf

¹⁵ <http://ec.europa.eu/research/horizonprize/index.cfm?prize=co2reuse>

The ETS is and remains the cornerstone of the EU policy to mitigate climate change. It covers about 45% of GHG emissions in the EU. To incentivise the transition to a low-carbon economy, the revised ETS will be accompanied by an Innovation Fund that is to provide financial support for *inter alia* renewable energy and CCU projects.

These Directives are relevant to the development of CCU because of the high energy need of CCU technologies, their potential to use and increase the share of renewable energies, and their potential to reduce CO₂ emissions. CCU can thus affect the achievement of their objectives.

Other legislation that is concomitant with the above Directives and constitutes the main CCU-relevant policy framework, in particular:

- The Monitoring and Reporting Regulation ('MRR') (601/2012) that sets out how GHG emissions are monitored and reported pursuant to the ETS directive;
- The Fuel Quality Directive ('FQD') (2009/30/EC) which establishes rules for the reduction of GHG and air pollutant emissions from fuels as well as rules to establish a single fuel market;
- The Effort Sharing Decision ('ESD') (406/2009/EC) and the proposal for the Effort Sharing Regulation ('ESR') (COM/2016/0482) that establish binding annual GHG emission targets for the period 2013-2020 (ESD) and 2021-2030 (ESR) for most sectors not included in the ETS Directive;
- The Land Use, Land Use Change and Forestry Decision ('LULUCF') (529/2013/EU) provides the framework to account for GHG emissions and removals related to agricultural land and forestry from 2021 onwards; the LULUCF Regulation was also agreed along with the ESR.

Apart from the above climate and energy framework that is of particular relevance to the energy and transport sectors, other policy and legislative clusters are relevant for CCU, in particular the following:

- Products and labelling policy framework that address the beginning-of-life which is relevant for establishing a circular approach together with the waste legislation that addresses the end-of-life of products (see below). CCU products still need to be (further) recognised under this legislation.
- Waste and circular economy policy framework that seeks to close the material loop via recycling and re-use of waste and the impact of waste on air, water and soil. It contains the EU Action Plan for a Circular Economy ('CEAP') (COM(2015)614). Incentives to close the carbon loop could come from this framework.

- Environmental pollution and risk policy framework in conjunction with the environmental impact assessment policy framework. The first framework aims at regulating and controlling emissions into air, water and land and preventing and mitigating environmental damage and accidents. The main instrument here is the Industrial Emissions Directive ('IED') (2010/75/EU) that has the objective to prevent, reduce and eliminate pollution from industrial activities and links to the ETS.
- Financing programmes and instruments that do or can finance CCU and which include Horizon 2020 and its successor FP9, the ETS Innovation Fund (see above), the LIFE Climate Action sub-programme and the European Fund for Structural Investments ('EFSI').

The EU has regulated the sectors where energy is used and CO₂ emissions occur, rather than the material or chemical sectors *per se* which are considered in this Opinion as well. Key to upholding the integrity of this framework is to ensure that a coherent GHG emission accounting system is in place for all major industrial sectors that are covered by the ETS Directive to avoid the risk of double counting.

4.2. Current Situation

No reliable estimates exist today for the total actual implementable savings of CO₂ emissions via CCU technologies. The amount of CO₂ that is useable varies with the technology employed and the energy to be spent for capture and conversion. Moreover, its future evolution depends also on the pace of the de-fossilisation of the economy.

A practical, rule-based Life Cycle Assessment (LCA) is required to assess the CO₂ savings of each technology and system, in particular as a basis for funding decisions. LCA should not only cover the emissions of the capture and conversion process *per se*, but also consider those of the material resources for the installations such as wind power generators. Moreover, the turn-over time of captured carbon is of importance too: the duration of storage in products determines the required intensity of re-capture and re-use to keep the cycle closed and CCU sustainable. LCA is also the basis to compare the CO₂ mitigation potential of alternative technologies and approaches and avoid double counting (von der Assen, Voll, Peters, & Bardow, 2014).

LCA calculations undertaken by the JRC in the context of the revision the RED II show that CO₂-based fuels have intrinsically a lower efficiency than e-fuels and that the GHG intensity of these fuels highly depends on the GHG intensity of the electricity used to produce them.

CCU technologies are at different stages of technological and system or integration readiness (expressed as TRL and SRL/IRL levels) - from laboratory and pilot testing, and commercial demonstration to market-maturity. Improvement of technologies will increase their efficiency, reduce costs, energy and materials consumption, and will require demonstration at large scale and in different settings.

International climate obligations require reliable monitoring and reporting of real and calculated GHG emissions. Currently, the EU ETS provides derogation from GHG emissions accounting only for CCS in accordance with the Directive on the geological storage of CO₂. Process CO₂ is accounted as 'emissions' under the ETS Directive and attributable to the manufacturer even when captured, transferred and converted into CCU products. Although the understandable motive is to avoid potential loopholes in CO₂ accounting under the ETS, this ignores the fact that CO₂ is not directly released to the atmosphere, but delayed for a shorter (CCU fuels) or longer period (chemicals and materials such as polymers). A methodology can be challenging to develop but is necessary to account for emissions from the use of CCU products, to incentivise investment in CCU technologies whilst ensuring that resulting emissions are counted exactly once.

This situation reflects the novelty of CCU technologies, the multitude of different products and of end-of-life scenarios. ETS focuses on reducing the release of carbon at point sources, and is not equipped to account for carbon emissions across sectors and considering the life cycle of a product with the sole exception of storage in a geological storage site. A judgement of the European Court of Justice in case C-460/15 (Schaefer Kalk)¹⁶ may require that the situation is reconsidered, in particular where carbon originates from industrial GHG emissions and is bound in a chemically stable manner (in this case: precipitated calcium carbonate). As long as CO₂ is sequestered and not released in the atmosphere during the lifetime of the CCU-product, it should *not* be considered to be emitted by the installation producing the CO₂.

At the time of writing, a recast of the Renewable Energy Directive (RED II) is being negotiated by the EU co-legislators. The Directive intends to increase the amount of renewable energy (REN) in final energy consumption and reduce emissions. The kind of CCU fuels that will be covered and the conditions for their production are unclear at this moment. The availability and allowed use of renewable energies will determine whether CCU fuels can compete with other uses of those energies such as de-fossilisation of the grid or direct electrification.

The Fuel Quality Directive (FQD) allows in principle CCU-fuels to contribute to the target of reducing the GHG intensity of transport fuels in 2020. However, this would require the definition of default values for such fuels under a Delegated Act¹⁷. The adoption of this Delegated Act was put on hold after agreement on the RED II in order to align, in particular, the rules for counting renewable electricity for the production of CCU fuels.

¹⁶ http://eur-lex.europa.eu/legal-content/en/TXT/PDF/?uri=uriserv%3AOJ.C_.2017.070.01.0006.01.ENG

¹⁷ A Delegated Act is a non-legislative act of general application that supplements or amends certain non-essential elements of a legislative act (see Article 290 of the TFEU). The EU legislator, i.e. the European Parliament and the Council, delegate the drafting and application to the Commission the power to adopt non-legislative acts of general application that supplement or amend certain non-essential elements of a legislative act. <http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=LEGISSUM:ai0032&from=EN>

CO₂-based renewable fuels are further incentivised by the Indirect Land Use Change Directive that amended the RED and FQD and that introduces into the RED an indicative target for advanced biofuels, including CO₂-based fuels, as a reference for national targets.

The deployment of Direct Air Capture (DAC) to close the carbon loop is not yet covered by legislation. Its large-scale deployment would have a considerable impact on the renewable energy available for other uses as well as on the contribution which CCU could make to sustainably remove CO₂ from the atmosphere.

No legislative equivalent to RED and FQD exists for (renewable) chemicals and materials. The deployment of CCU in that context could help Member States to meet targets under the ESR because it allows the substitution of fossil feedstock by renewable ones (see above). The X-prize CO₂ emissions challenge¹⁸, for instance, shows that relevant contributions can be made in these fields.

The EU climate change mitigation endeavour triggered an effort to de-fossilise the economy. CCU allows fossil carbon to be left in the ground, and closing the carbon loop above the ground, starting with high-density CO₂ streams from industrial processes and progressively moving towards capturing less dense sources. The successful deployment of CCU as an approach to contribute to climate change mitigation requires investment in low-carbon energies, dedicated research to increase TRL and IRLs, and a legislative and investment framework that can be informed by a robust methodology for the assessment of benefits along the whole life cycle of the process and products.

¹⁸ <https://carbon.xprize.org>



Scientific Evidence

5. SCIENTIFIC EVIDENCE

Most of the scientific evidence drawn on is contained in the SAPEA Evidence Review Report (SAPEA ERR) (SAPEA, 2018). The Opinion also draws on other key scientific evidence, workshops discussions and ad-hoc consultations with experts and stakeholders on the potential climate benefits of CCU.

5.1. What does Carbon Capture and Utilisation (CCU) stand for in the scope of this Opinion?

In this Opinion CCU stands for the capture of anthropogenic CO₂ and its subsequent use in a synthesis process, transforming CO₂ into another product with commercial value. It is noted that CCU processes may use CO₂ not only from power plants or energy intensive and heavy industries, but also CO₂ present in the air (Pérez-Fortes & Barbosa, 2016). A CO₂ capture technology includes the Direct Air Capture of CO₂ (DAC) from the air in which the concentration of CO₂ is quite dilute, i.e., approximately 0.04 mol% (400 ppm) but also its capture from the exhaust of a power plant, in which its concentration is on average 12 mol% (Wilcox, 2014).

The CCU field is heterogeneous, covering a wide range of technologies and products, and a wide range of diverse actors and industries (Hendriks, Noothout, Zakkour, & Cook, 2013).

It is also important to note that when CO₂ utilisation has traditionally been discussed, this has been in the context of CO₂-Enhanced Oil Recovery (CO₂-EOR) in the United States (Mac Dowell, Fennell, Shah, & Maitland, 2017), which is not in the scope of this Opinion.

A CO₂ value chain involves production of CO₂ (involving capture and purification); technologies that convert CO₂ and other materials into valuable products; sourcing of low-carbon energy to drive all of the transformation processes required to convert CO₂ to products (including production of hydrogen, syngas, methane etc.); transport of energy and materials to where they are needed; managing inventory levels of resources, and delivering the products to customers; all in order to create value - economic, environmental, social etc. (Jarvis & Samsatli, 2018).

The SAPEA ERR (SAPEA, 2018) points out that when viewed from a system perspective, CCU is a system consisting of at least five steps:

1. Source of CO₂;
2. Capture of CO₂ from an exhaust stream, or directly from air;
3. CO₂ conversion to a Carbon-rich (C-rich) chemical product (where in most cases the carbon atom is in a reduced state with respect to its fully oxidised state in the original CO₂ molecule);

4. Utilisation of the C-rich product (to deliver a service to society, e.g. by burning the fuel to provide propulsion);
5. Disposal of the Carbon atom, either by disposing of the product as such (e.g. in a landfill) or by disposing of the relevant decomposition products, typically CO₂ again or another Greenhouse Gas (GHG) such as methane.

Typically, step 2 is a chemical process that is endothermic and endergonic, requires hydrogen as co-reactant. In summary we can say that CO₂ conversion involves at least 3 elements: (1) harvesting of required C-free renewable energy (RES); (ii) synthesis of green-H₂ via water electrolysis powered by RES and (iii) CO₂ conversion via reaction with H₂. Figure 4 shows a schematic of typical CCU systems.

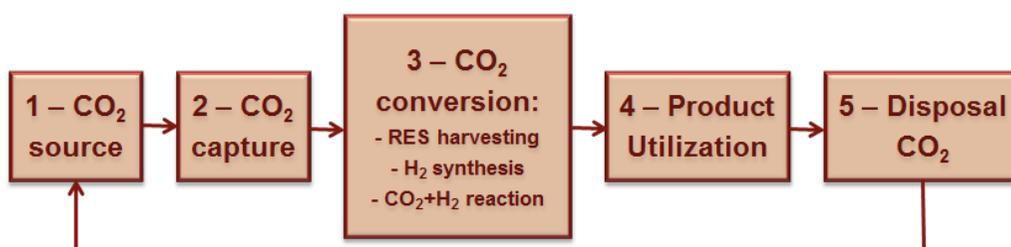


Figure 4 - Schematics of CCU systems (SAM secretariat)

The time interval (t_{LIFE}) between CO₂ utilisation (step 4 above) and carbon disposal (step 5 above) can be either a few days (fuels), or a few months (urea), or decades (some polymers). It is also worth noting that most of the technological building blocks of a CCU system belong also to other technology chains of interest for climate mitigation, e.g. post-combustion CO₂ capture is a cornerstone of CO₂ Capture and Storage (CCS) (SAPEA, 2018).

CO₂ is considered to be a thermodynamically and chemically stable molecule under standard conditions, it can under certain conditions react with other chemical feedstocks given sufficient energy and using a catalyst to produce value added commodity chemicals, fuels and materials (Styring, Jansen, de Coninck, Reith, & Armstrong, 2011). CO₂ utilisation is not a recent fact. There has been active interest in the chemical conversion of CO₂ into chemicals, plastics and fuels since the 1850s with the synthesis of salicylic acid, sodium carbonate and urea (Mac Dowell et al., 2017)

CCU involves also a network of technologies and infrastructures (such as conversion, transportation and storage) along with its associated activities (such as sourcing raw materials, processing, logistics, inventory management, waste management) required to convert low-value resources to high-value products and energy services and deliver them to customers (Jarvis & Samsatli, 2018).

There are many C-rich chemical products that could be synthesised via CCU, e.g. synthetic fuels, both liquid (such as methanol) and gaseous, typically Synthetic Natural Gas (SNG), urea (via reaction with ammonia, which is in turn made using H₂), or higher molecular weight organic compounds. Most of these products are obtained from fossil fuels (that provide a reduced carbon atom) either via separation or through reactions that are either exothermic or much less endothermic than the corresponding reactions using CO₂ as feedstock, urea being a noticeable exception to this general rule (SAPEA, 2018).

Figure 5 illustrates most of the current and potential uses of CO₂. However, many of these uses are small scale and typically emit the CO₂ to the atmosphere after use, resulting in no reduction in overall CO₂ emissions.

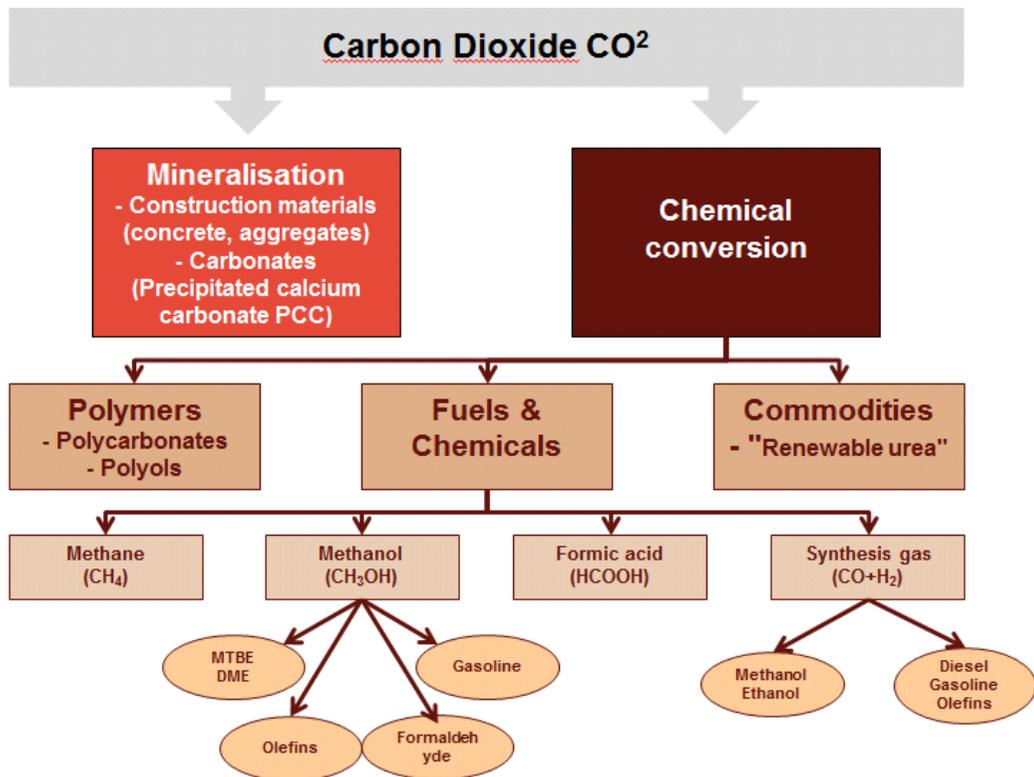


Figure 5 – Main CO₂ utilisation routes and applications (adapted from BioCO₂ project¹⁹).

5.2. CCU and the energy systems

CO₂ is the lowest energy state of any binary neutral carbon species and the ultimate product of energy-releasing hydrocarbon combustion. Therefore, a significant energy input is required to overcome the substantial thermodynamic and kinetic barriers of converting CO₂ into a useable fuel. CCU technologies may be used to provide energy storage or enhance the performance of existing energy

¹⁹ <http://www.vtt.fi/sites/BioCO2/en>

generation systems. For example, captured CO₂ may be used as a form of energy storage through its synthesis with hydrogen so as to produce methane or methanol, potentially providing a useful source of off-peak demand in systems dominated by renewables such as geothermal or wind (SAPEA, 2018).

5.3. CCU and CO₂ process emissions

In the industrial sector (such as for example in the production of cement or steel) some CO₂ sources are related to the process chemistry rather than the combustion of hydrocarbons to drive the process, where at this moment these emissions cannot yet be avoided in an economic viable way. In these industrial sectors CCU may be part of the different technologies needed to reduce their CO₂ emissions.

5.4. CO₂ uses and the period during which it will remain bound

CCU technologies bind the CO₂ molecule in a multitude of different products for different periods of time. The lifetime in which CO₂ is removed from the carbon cycle will vary: some uses, such as the use of CO₂ as a fuel precursor are very short term (days to months); whilst others, such as its use as a precursor for plastics, have a longer term. In fact, the use of CO₂ as a precursor for some plastics may result in the CO₂ being fixed away from the atmosphere for decades and can, therefore, be considered a form of storage (Boot-Handford et al., 2014).

Table 1 identifies the average lifetime for some products obtained by CCU.

Table 1- Potential for CO₂ utilisation and lifetime adapted from (Styring et al., 2011).

Product	Annual market (Mt/yr)	Lifetime
Urea	100	6 months
Methanol	40	6 months
Inorganic carbonates	80	Decades to centuries
Organic carbonates	2.6	Decades to centuries
Poly(urethane)s	10	Decades to centuries

The production of fuels from CO₂ fits within the trend toward low carbon fuels and they represent one of the largest potential markets for CCU technology given the many global initiatives for greener alternatives. Figure 6 illustrates the potential for some products with a higher demand for methane (SAPEA, 2018).

Another major environmental driver for CO₂ utilisation is the provision of a non-fossil carbon feedstock for the chemical industry which may help to reduce depletion of resources.

Large quantities of CO₂ are already consumed through reaction with ammonia from the process to produce urea, a key ingredient in fertilisers. This is an established and commercially viable technology that already produces the annual global supplies of urea, and is therefore a saturated market. There is considerable scope for the production of diverse derivatives which themselves are useful feedstocks in the pharmaceuticals, fine chemicals and polymer industries (SAPEA, 2018).

Synthesis of organic carbonates from CO₂ is one of the largest opportunities for the use of CO₂ in industrial chemistry. CO₂ can be used as a feedstock to produce a large array of fine chemicals, either to be used directly by copolymerisation or indirectly by transformation of building blocks which were obtained from CO₂ in a previous step (Global Roadmap for Implementing CO₂ Utilization – ICEF).

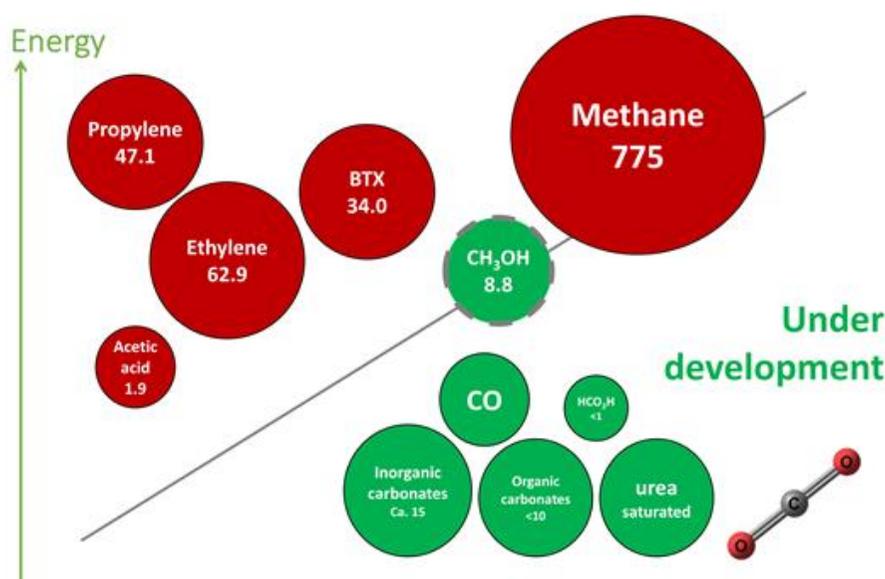


Figure 6 - Maximum potential of conversion of CO₂ into chemicals, in Europe. Numbers represent the equivalent CO₂ volumes required for production covering the consumption of a given chemical in the EU, in MtCO₂/yr (SAPEA, 2018).

Cyclic carbonates with more than six atoms can be ring-opened to give a hydroxy carboxylic acid that can be polymerised to give a poly(carbonate). Poly(carbonate)s are used extensively in construction materials in place of glass and in security and personal protection products due to its high strength and impact resistance while being extremely light and mouldable (Styring, 2011).

CO₂ utilisation by mineral carbonation mimics the naturally occurring rock weathering which is known to have played an important role in the historical reduction of the CO₂ concentration in the atmosphere after the creation of the earth (Styring et al., 2011). Mineral carbonation involves reaction of minerals (mostly calcium or magnesium silicates) with CO₂ into inert carbonates. These carbonates can then be used for example as construction materials.

5.5. The cyclical approach to CCU in the transition to a low- carbon economy

Decarbonisation is one of the main goals of the EU energy system and industry²⁰ and for that multiple actions and instruments are needed, and CCU may be a possible enabling technology for this purpose.

By utilising CO₂ it is possible to retain carbon within a cycle, longer or shorter depending on the time it is bound. It may be that the carbon is bound in a long term form, such as through mineralisation, to produce construction materials and polymer formation, or short term form stored within an energy vector, such as a synthetic liquid fuel (Mac Dowell, 2016). However, with conversion to fuels, capture of CO₂ from the air would ultimately be necessary to maintain the cycle.

From the analysis of these technology chains, some key conclusions can be drawn (for more details see SAPEA Report 2018): CCU may be part of a circular economy scheme where carbon atoms are recycled and re-used indefinitely over a long time scale. However, it is neither an indispensable element, nor is it sufficient, for a circular economy. True circular schemes are enabled only when the CO₂ generated from burning recycled synthetic (de-fossilised) fuel in centralised plants or in distributed facilities is again captured from the flue gas (post-combustion capture) or from the ambient atmosphere (direct air capture). CCU is not part of any negative emission technology chain, whereas CO₂ capture is; the pros and cons of using biomass instead of fossil-C or of converted CO₂ can be highlighted in the context of this analysis (SAPEA, 2018).

5.5.1. Direct air capture technology

Direct air capture (DAC) is the process of removing CO₂ from the air and generating a concentrated stream of CO₂ for use or storage.

Direct air capture of CO₂ involves a system where air from the atmosphere flows over a contactor that selectively removes the CO₂, which is then released as a concentrated stream for disposal or use, while the sorbent is regenerated and the CO₂-depleted air is returned to the atmosphere (EASAC, 2018). The main potential technologies involve liquid absorbents or solid adsorbents.

²⁰ Priority policy area - Climate action - decarbonising the economy
https://ec.europa.eu/commission/priorities/energy-union-and-climate/climate-action-decarbonising-economy_en

5.6. CCU in the context of societal services

CCU alone cannot realistically remediate all emissions because of the volumes involved and the potential markets for the individual products (see Figure 7). Therefore, the potential climate benefits of CCU have to be also assessed in the context of societal services, that can be provided by different energy carriers through technology chains that may include CCU or not (SAPEA, 2018):

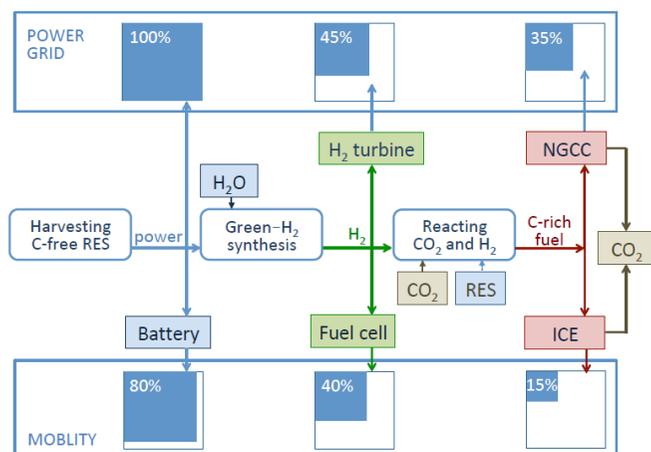
- i. Power generation and distribution through the grid;
- ii. Fuels (and power) for transport and mobility;
- iii. Storage and transport of renewable energies, to cope with their intermittency;
- iv. Manufacturing of industrial products.

Possible energy carriers are for simplicity electrons (i.e. electricity), hydrogen and a C-rich synthetic fuel, which can be SNG or a liquid fuel depending on the application (numerical examples are based on SNG).

The SAPEA ERR (SAPEA, 2018) aimed at an unbiased comparison of the different options and technology chains, based on a system analysis within well-specified system boundaries. In doing so these five criteria were used, namely:

1. Efficiency in the use of energy, particularly of carbon-free renewable energy;
2. Carbon fluxes, with reference to CO₂ emissions first, as well as to consumption of fossil-carbon resources and to occupation of sub-surface CO₂ storage space;
3. Environmental impact, on top of those considered within criterion 2;
4. Costs, including operational and capital costs, as well as financing schemes;
5. Societal perception and political feasibility.

Figure 7 – Multiple ways to provide power and mobility services using electricity, H₂ and SNG. Percentage numbers are estimates of the full-chain energy efficiency (SAPEA 2018).



5.7. CCU Climate mitigation potential

Information on the environmental performance of CCU technologies is currently limited and scattered. There are some studies (Abanades, Rubin, Mazzotti, & Herzog, 2017) that assess the climate change mitigation potential of CCU applications based on Life Cycle Analysis (LCA), but the approach is not coherent with the monitoring and reporting framework that is applied within the large installations that are covered by the Emissions Trading Scheme (EU ETS), which is based on annual monitoring, reporting and verification of emissions from each specific installation at the site of the installation.

The absence of such an approach reflects the novelty of the technologies as well as the multitude of different products and end-of-life possibilities.

Life Cycle Assessment (LCA) can be used to quantify the environmental impacts of products or services. It includes all processes, from cradle-to-grave, along the supply chain of the product or service.

In addition, the most promising CCU technologies appear to require significant amounts of energy. This means that even in situations where an LCA could potentially capture relevant impacts for a CCU technology, the climate mitigation potential, in particular, would also depend on the availability of low-carbon electricity, the efficiency of the technologies, the greenhouse gas intensity of inputs, how long and stable the CO₂ remains bound in its new form, and what products are replaced.

LCA should not only be limited to impacts on climate change. Instead, a wide range of environmental impacts should also be considered to avoid problem shifting to other impact categories such as resource depletion (Bui et al., 2018).

LCA needs to be complemented by a methodology to quantify emissions reductions. Internationally recognised standards to quantify emission reductions are key for environmental integrity. Methodologies are essential to quantify real and accurate emission reductions and help to establish the process of monitoring and verification of the emissions when the project is built. Methodologies of this kind have been developed under the UNFCCC and the Kyoto Protocol.

For example, methodologies for CDM projects (Clean Development Mechanism <https://cdm.unfccc.int/>) have been developed for a wide range of activities and technologies (see <https://cdm.unfccc.int/methodologies/index.html>) under the scope of the UNFCCC. The Clean Development Mechanism (CDM) is one of the Flexible Mechanisms defined in the Kyoto Protocol (IPCC, 2007) that provides for emissions reduction projects which generate Certified Emission Reduction units (CERs) which may be traded in emissions trading schemes.

A brief description of the structure of the Methodologies applied in CDM projects may be found in <https://cdm.unfccc.int/Projects/pac/howto/CDMProject-Activity/NewMethodology/index.html>.

Inspired by these methodologies the Opinion proposes a methodology that will provide a baseline for climate benefit calculations and will quantify the Climate Mitigation potential resulting from long term operated CCU activities based in existing methodologies that are used for climate-friendly technologies under the ambit of the UNFCCC (for example the methodologies used for the assessment of the CDM – Clean Development Mechanism projects of the Kyoto Protocol).

The proposed methodology needs to include the following four components:

1. **Method to assess the environmental integrity of the process:** Methodologies are essential to quantify real and accurate emission reductions. They also help monitor, quantify and accurately estimate emissions once a project is built. Eligible certified emission reduction units are determined by the difference between the baseline and actual emissions. The method would also contain a set of MRV (monitoring, reporting and verification) standard and transparent rules applicable to different CCU applications.
2. **Simplified Life Cycle Assessment (LCA):** The development of an operational "rule-based LCA methodology" that considers all the relevant energy flows for CCU processes in a systemic approach is recommended. To enable quantitative estimates of GHG emissions from cradle-to-grave requires a clear and detailed definition of all the subsystems within the CCU system, following a standardised and transparent LCA methodology for the different CCU applications.
3. **Matrix with positive and negative externalities:** The development of a matrix with possible positive and negative externalities with their quantification, such as, the contribution of the CCU for the circular economy, industrial policy, jobs. This matrix should take into consideration that CO₂ is a source (raw material) of potential valuable materials, products and services. Examples of negative externalities may be environmental impacts such as water use or increased need of materials, energy and land.
4. **Demonstration of 'Additionality':** The demonstration of Additionality (to avoid investing in projects that would have happened anyway) is required by adopting specific rules that define and quantify the additionality of a CCU project. In that manner it can be ensured that the project emits less CO₂ than without the intervention of the project.

The demonstration of the Additionality of a CCU project needs to include the identification of alternative scenarios to the project, the analysis of barriers and the investment analysis. In the investment analysis, the total abatement costs should be considered. Marginal abatement cost is a method of financial analysis which is good for a first shallow decarbonisation phase, while CCU is expected to be competitive only in deep decarbonisation phase, calling for the application of total abatement costs of the whole energy system.

5.8. Novel CCU Technologies

Research into the utilisation of CO₂ has been ongoing since the beginning of the XX century but a renewed interest was observed with the growing awareness of the impact of CO₂ as a greenhouse gas (Styring, 2015). CCU technologies are at different stages of technological readiness - from laboratory testing to commercial demonstration (Alberici et al., 2017).

CCU technologies face today a range of technical, environmental and economic challenges and research in novel technologies can overcome some of these challenges. Technology improvements to increase efficiency, to reduce energy and materials consumption and to prove the technologies at large scale and in different settings are needed.

The EU Commission has provided a wide range of research and development grants in the field of CCU (European Commission, 2018). The research includes for instance CO₂ catalytic science, novel CO₂ reaction pathways, novel reactor designs and the translation of this research into breakthroughs in processes.

The quality and quantity of CO₂ could also be a challenge. CO₂ needs to be captured, concentrated and purified before it can be used at least for some of the processes. This can be energy intensive and costly. However, certain industrial processes offer nearly pure CO₂ and some conversion technologies can use the flue gases without much purification or concentration. The volumes of available CO₂ may not match the needs of utilisation unless clusters of capture, utilisation and storage are developed.

Large scale uses of CO₂, for example to manufacture fuels and commodity chemicals, will require significant amounts of green hydrogen. For uses that do not involve hydrogen, such as manufacturing polymers, mineral carbonates, and novel materials, the scale of CO₂ used is smaller but offer a higher value. As an example it is possible to convert CO₂ from the air into carbon nanofibers by using an efficient, low cost electrochemical process.

Carbon nanofibers are increasingly being used as a structural material on the aerospace, automotive, and other industries, which value its strength and low weight. These novel products may create completely new markets. Their potential should be studied.

There are also barriers to CCU implementation. An obvious barrier is the unfavourable thermodynamics of many conversions that means that there will be an energy cost associated with utilisation. A second issue is supply capacity, both in terms of co-reactants in any process and also in market demand for the product.

Despite the fact that CO₂ is a widely available, low-cost and low-toxicity C₁ feedstock, current industrial demand is relatively low, amounting to around 232 Mt per year, with only a few commercial processes currently using CO₂ as a raw material (Boot-Handford et al., 2014). CO₂ is currently used in the production of methanol and urea for the bulk chemical industry and in salicylic acid and cyclic

carbonates production. These processes are well-established but the implementation of new CO₂ utilisation technologies, scaling up from laboratory scale to pilot to production plant has been relatively slow.

Some mineralisation pathways are already competitive (e.g. reacting CO₂ with industrial and municipal solid waste to produce building blocks) but their market potential is limited by the volume of waste or by the need for nearby sources of CO₂ and other raw materials.

The quality and quantity of CO₂ could also be a challenge. CO₂ needs to be captured, concentrated and purified before it can be used at least for some of the processes. This can be energy intensive and costly. However, certain industrial processes offer nearly pure CO₂ and some conversion technologies can use the flue gases without much purification or concentration. The volumes of available CO₂ may not match the needs of utilisation unless clusters of capture, utilisation and storage are developed.

At present, the market for CO₂ is several orders of magnitude smaller than the amount of CO₂ released into the atmosphere each year from anthropogenic sources and approximately 60 times smaller than the amount of CO₂ emitted from large point sources (14 000 Mt per year) (Boot-Handford et al., 2014).

Figure 8 shows a comparison of the global anthropogenic CO₂ emissions and the potential of CO₂ utilisation. The estimated long-term potential is one order of magnitude and the current utilisation two orders of magnitude lower than the anthropogenic CO₂ emissions (Aresta, Dibenedetto, & Angelini, 2013; Assen, Müller, Steingrube, Voll, & Bardow, 2016). Currently the majority of the utilised CO₂ is used for synthesis of urea and inorganic carbonates and for improving methanol production. These applications, however, bind only the CO₂ that was released by earlier production steps. We would like to reinforce that, CCU alone will not solve the climate change problem but can still play a significant role - battling climate change calls for a combination of various technologies (Aresta, Dibenedetto, & Angelini, 2013; Assen, Müller, Steingrube, Voll, & Bardow, 2016) in order to reach the target for 2050.

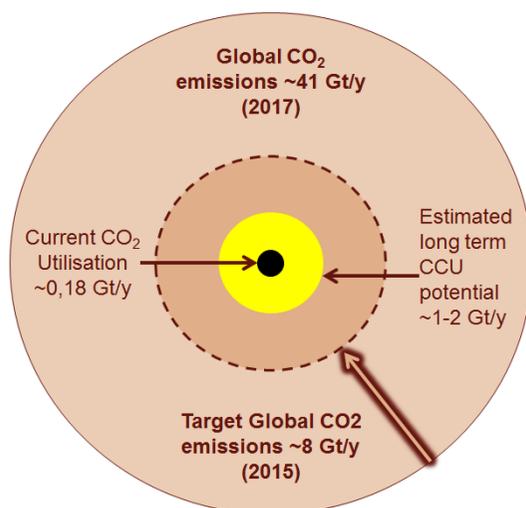


Figure 8 – Global CO₂ emissions and the role of CCU. The figure shows also the target global emissions for 2050 as well as a simplified estimation for the CCU potential including all the possible uses (simplified and adapted^{21, 22})

Novel Direct Air capture (DAC) technologies could also offer an option for addressing CO₂ emissions from mobile and distributed sources, such as vehicles, fuel use in buildings and geographically isolated industry, where direct capture would be either impractical and/or uneconomical. However, there are also significant disadvantages to the technology. Removing and concentrating CO₂ from air to a pure stream implies a greater energy input, and treatment of a vastly greater volume of gas than CO₂ capture from concentrated point sources.

A driver for investment in carbon dioxide utilisation will be the ability to maintain security in the supply of fuels and commodity chemicals that have traditionally relied on petrochemical feedstocks. Petrochemical prices are indexed to crude oil prices and fluctuation can lead to supply and price instabilities.

Capturing CO₂ is associated with high upfront investment costs, highly variable operating costs and in most cases leads to a significant energy penalty. Furthermore, due to the energy penalty with CCU, it is likely that the conversion steps will take place at times of low energy demand, when renewable electricity is comparatively cheaper.

Other factors that govern the commercial viability of CCU also need to be considered. These include the availability of hydrogen and other feedstocks in the supply chain and a systems approach to integration of resources, energy and land use.

²¹ <http://www.vtt.fi/sites/BioCO2/en/english>

²² http://www.globalcarbonproject.org/carbonbudget/17/files/GCP_CarbonBudget_2017.pdf

*STATEMENTS AND
RECOMMENDATIONS*

6. STATEMENTS AND RECOMMENDATIONS

The Group of Chief Scientific Advisors states that:

Statement 1 - CCU timeline advancing the low-carbon economy

De-fossilisation of the economy is one of the main climate action goals of the European Union; multiple policy actions, instruments and technologies are needed to move towards that objective and CCU may be seen as an enabling option for this purpose.

CCU is a suite of technologies presenting many uncertainties mainly due to the barriers to their deployment such as the energy penalty, need of C-free RES and currently low TRL (Technology Readiness Level) of the novel technologies. Policy uncertainty may also undermine the effectiveness of measures in supporting the deployment of CCU projects, mainly those using novel technologies with high CAPEX investments.

Taking into consideration these constraints, the role of CCU may be seen as:

- In the medium term (2030/40) - making use of the CO₂ molecule a second time can contribute to the transition towards a low carbon future (mainly in energy, transport and industrial sectors) provided that the available energy inputs are low-carbon.
- In the medium (2030/40) - may provide a contribution to reduce the carbon footprint of processes that are currently difficult to decarbonise due to their process emissions or high demands of energy, notwithstanding the development of alternative breakthrough technologies.
- In the medium (2030/40) and long term (2050 and beyond) - may contribute to the de-fossilisation of the energy and transport systems [by using excess variable renewables] to store in fuels for the use in high energy density needs (long haul flights and long distance shipping) as well as possible storage medium for power system.

Statement 2 - R-CCU: CCU and Renewable Energy Sources (RES)

CCU systems require large quantities of low carbon, as well as affordable and highly available energy. Therefore, CCU has little potential to mitigate climate change, unless the energy needed for the overall CCU process comes from low carbon sources to avoid increasing CO₂ emissions from the processes.

To contribute to climate change mitigation, in particular in the case of e-fuels, renewable energy, such as surplus renewable electricity (REL) should be used across the whole life cycle.

Statement 3 - CCU: beyond direct climate mitigation

The climate change mitigation potential of CCU as a service to energy or industrial systems should be seen not only in terms of CO₂ emissions reduction but also in terms of CCU as a service to larger production systems, e.g.:

- Storage medium of renewable, variable energy
- Providing alternative to non-electricity energy vectors (e.g. synthetic fuels for aviation or maritime sector);
- Exploitation of existing distribution infrastructures may ease the transition to de-fossilisation, especially for the transport sector;
- Re-use of industrial effluents or other sources of CO₂ emissions to manufacture carbon-containing industrial products (materials and chemicals).

An example of a positive externality of CCU could be envisaged in the case of the use of synthetic fuels that would be nearly carbon-neutral, and which could replace gasoline and diesel in road transport. The synthetic fuels would be used in internal combustion engines. Synthetic fuels could be used in existing vehicles and refuelling infrastructures with small adaptations. However, this should be seen as a possible transition measure and a thorough assessment should be performed in order to avoid a delay in the development of the low carbon new technologies that would result in a loss of competitiveness of the European automotive industry.

The production of synthetic fuels for road transport using CCU may constitute an example where the CO₂ mitigation potential is small but the externalities are highly valuable in terms of keeping jobs and offering a better solution for the use of the existing cars with small adaptations.

Statement 4 - CCU for the production of chemicals

The utilisation of CO₂ as a raw material constitutes a technological change for the chemical industry and this implies in most cases substantial investment. These technologies may have to compete against processes that are highly efficient and cost competitive. The use of CCU technologies contributing to a low-carbon and circular economy will therefore require an adequate policy framework with assessment of the environmental added value of the chemical valorisation of CO₂.

For example, affordable access to renewable energy and the development of processes to generate renewable hydrogen at competitive cost are important elements for the use of CCU in the production of chemicals as well as capture of the CO₂ emitted after use of the final product.

Statement 5 - CCU for the production of materials

CO₂ has been used to manufacture polymers, such as polycarbonates and polyurethanes. The polymers may comprise 30 to 50% by mass CO₂ in the polymer backbone. Polymer products made from CO₂ are being already commercialised by various companies. One of the main advantages of these materials is related to wide range of performances and functionalities suitable for several applications, especially where sustainability is an important product attribute. Another advantage deals with the fact that, polymers obtained from CO₂ can be produced and processed using the existing infrastructure for petrochemical based polymer manufacturing.

The conversion of CO₂ into carbonates may offer a potential to convert low-value materials into useful products, namely concrete, asphalt and construction fill.

Statement 6 - CCU and CO₂ processes emissions

There are examples in the industrial sector (such as for example in the production of cement or steel) where at this moment CO₂ emissions cannot yet be avoided in an economically viable way by energy efficiency measures or fuel switch. In these cases CCU has the potential to be applied along with other emission reduction technologies to minimise costs and optimise energy and material flows.

Statement 7 - Period of time that CO₂ will remain bound

The origin and use of CO₂ may determine the climate change mitigation potential of different CCU systems. The utilised CO₂ is in most cases re-emitted at a later point in time. CCU resulting products are also of very different natures and have different lifetimes. In the case of fuels CO₂ is bound in the time scale of days/weeks, chemicals in the time scale of decades and in materials of centuries.

However, if a cyclical approach (i.e. application of DAC (Direct Air Capture) to offset all process-related and end-use emissions) is adopted, the period of time that CO₂ will remain bound is less relevant.

Statement 8 - The cyclical approach to CCU

A non-fully circular, i.e. non-sustainable deployment of CCU technologies, only delays the CO₂ emissions to the atmosphere for a time scale that it is dependent of the application. A product produced by a CCU technology and that releases its carbon content as CO₂ in a short time (days, weeks, months, or even decades) can thus not mitigate climate change unless the released CO₂ is sustainably captured back by DAC (Direct Air Capture).

Therefore CCU may contribute to establishing a circular economy and reaching climate mitigation goals under the conditions set out in this Opinion. In that case, CCU may be an important component for a policy approach to decarbonise the economy, in the medium to long term.

The Group of Chief Scientific Advisors recommends:

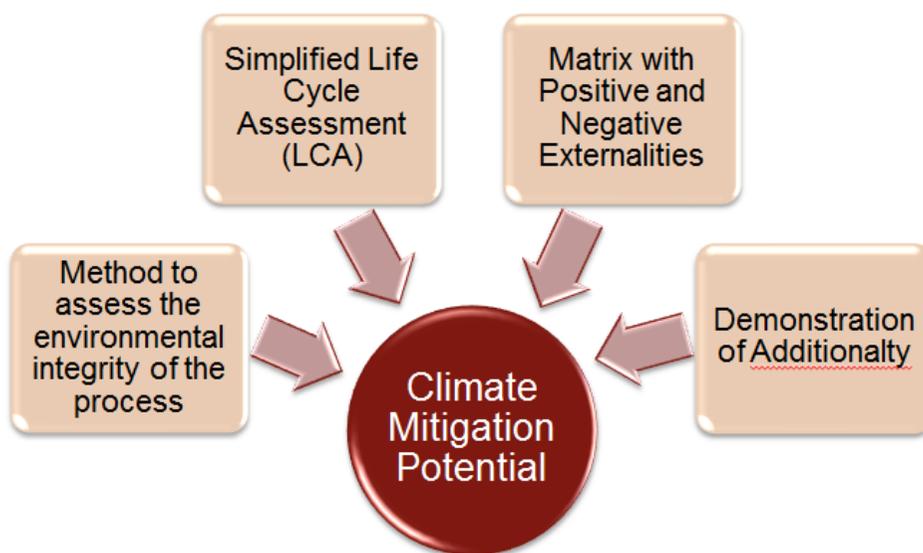
Recommendation 1

To develop a methodology to calculate the Climate Mitigation potential of CCU

It is strongly recommended that European Commission develops a rigorous cross-sectorial and systematic methodology to calculate the CO₂ Climate Mitigation potential of CCU projects.

Such a methodology should be preceded by the analysis of technologies (including simplified and operational LCA assessment) required to achieve deep decarbonisation. Only projects that are beneficial to close gaps to achieve deep decarbonisation should be taken into account. The eligibility criteria for CCU projects are described in Recommendation 2.

This will constitute a powerful set of European guidelines and standards for the analysis of CCU projects.



Recommendation 2

Eligibility criteria for CCU projects

A CCU project should be considered eligible for funding or to be further included in Climate Change Schemes, such as the Innovation Fund, if through the use of the described methodology, the project is able to demonstrate and to quantify its CO₂ mitigation potential.

It is advisable that for the CCU project, the four following conditions are fulfilled:

- The required energy has low-carbon origin, with high availability and low cost
- Other, simpler and more cost effective solutions do not yield comparable products available in sufficient quantities
- The readiness level of CCU projects will meet the objectives
- There are supplementary benefits of the CCU projects in addition to climate mitigation potential.

Recommendation 3

CCU Novel Technologies

CCU technologies cover a wide spectrum of different technologies with a variety of TRLs. Some of the technologies are at the research and laboratory experimentation level (e.g., the case of nanomaterial catalysts), others at the demonstration level (e.g., the production of renewable methanol) and some technologies are already mature and have entered in the market (production of chemicals such as urea). However, the majority of technologies are at a TRL 3-5.

CCU technologies are not stand-alone but part of a system. Both TRLs (Technology Readiness Levels) and IRLs (Integration Readiness Levels) should be considered to assess the readiness of and the contribution that CCU technologies can make.

Recommendation 4

Regulatory and investment framework

Due to the low TRL and the uncertainty about the mitigation potential, CCU technologies have been absent from the European and International Climate Change funding schemes. A stable regulatory and investment framework is necessary in order these technologies achieve a mature stage.

It is strongly recommended that European Commission develops a cross-sectorial and systemic regulatory and investment framework for CCU applications comprising a set of clear rules and operational guidelines for CCU applications.

Recommendation 5

International framework - Party to the Convention on Climate Change

The above methodology should be based on the described mechanisms indicated in this Opinion, and also be used as a selection criterion for CCU projects to be eligible in European and International schemes.

It is recommended that the European Commission advocates the methodologies of the Convention on Climate Change, the Kyoto Protocol and the Paris Agreement in international arenas, in particular in the scope of the UNFCCC.



Annexes

ANNEXES

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Annex 1 – List of Contributing Experts and Stakeholder representatives consulted

The experts consulted for this Opinion have attended the 'Novel carbon capture and utilisation technologies: research and climate aspects, Scientific Expert Workshop', hosted by SAPEA²³ (25 January 2018, Palais des Academies, Brussels), or the 'Novel carbon capture and utilisation technologies: research and climate aspects, Stakeholders meeting', organised by the European Commission (20th February 2018, Brussels, CDMA Building, rue du Champ de Mars, 21, Brussels – see annex 3)

²³ www.sapea.info/carboncaptureworkshop

Annex 2 – CCU Scoping paper

Scientific Advice Mechanism

Scoping paper:

Novel carbon capture and utilisation technologies: research and climate aspects

27 June, 2017

Issue at stake

A number of novel Carbon Capture and Utilisation (CCU) technologies are under development for the production of low-carbon fuels, chemicals and building materials. They use CO₂ as a feedstock, therefore storing it in products temporarily or for longer periods of time. These technologies are subject currently to important policy debates as they may offer a promising potential for decarbonisation, industrial innovation and competitiveness of energy-intensive industries.

However, CCU technologies face a range of technical, environmental and economic challenges. Research in novel technologies can overcome some of these challenges. Their climate mitigation potential is as yet unclear, as it is dependent on a number of factors, which may be specific to each technology and resulting conversion product, as well as the location and characteristics of the installation.

Based on existing research, the climate mitigation and economic potentials of CCU technologies need to be carefully considered from a scientific point of view to inform future policy decisions in this field, including financial support. In particular, there is a need to ensure that support is limited to technologies that are environmentally-safe and provide substantial climate benefits.

Policy context

The CCU technologies should be placed in the broader context of the implementation of the Paris Agreement. The EU has committed to an economy-wide domestic target of at least 40% greenhouse gas (GHG) emission reduction for 2030 compared to 1990. Implementing the EU 2030 energy and climate framework is a priority in follow up to the Paris Agreement.

The Commission has therefore tabled a number of proposals for revising the current regulatory framework, *inter alia* legislative through proposals on the EU emissions trading system (EU ETS), on an Effort Sharing Regulation setting national 2030 GHG targets. *The Clean Energy for All Europeans package*²⁴ also

²⁴ <http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1485341914564&uri=CELEX:52016DC0860%2801%29>

contains proposals to revise the Renewable Energy and the Energy Efficiency Directives. All these proposals are currently subject to co-decision.

Carbon Capture and Utilisation fuels can be supported under the current Fuel Quality Directive and in future under the Renewable Energy Directive provided they deliver greenhouse gas savings.

Shifting and rapidly scaling up private investment is essential to support the transition to a low emission and climate resilient economy, and for avoiding the "lock-in" of high emissions infrastructure and assets.

EU funds will play an important role for mobilising the markets. In the proposal for a revised EU ETS, the Commission has proposed an Innovation Fund to extend existing support for the demonstration of low carbon innovative technologies to breakthrough innovation in industry. Carbon capture and utilisation technologies will be in principle eligible but the selection criteria still need to be determined in the implementing legislation. One important selection criterion for any of the technologies supported will be the climate mitigation potential.

Current situation

For the purpose of this scoping paper Carbon Capture and Utilisation is defined as those technologies that use CO₂ as a feedstock and convert it into value-added products such as fuels, chemicals or building materials.²⁵

These CCU technologies may offer a range of potential opportunities for European industry and the pursuit of European Union policy objectives, including:

Supporting climate change objectives, by replacing crude oil and gas in chemicals and fuels but also through fixation of the CO₂ in materials;

Supporting the circular economy, by converting waste CO₂ to products, industrial innovation and competitiveness, particularly important for energy-intensive industries, developing new and more efficient processes and creating new market opportunities;

Supporting energy security and renewable energy deployment, through utilising excess renewable electricity and providing energy storage alternatives;

Supporting the evolution of CO₂ capture systems, which may help deployment of CCS²⁶ technology, which in turn provides permanent and large-scale storage of CO₂.

CCU technologies are however at different stages of technological readiness - from laboratory testing to commercial demonstration. Technology improvements to

²⁵ Technologies that use CO₂ as a working fluid or solvent such as for enhanced oil recovery or in supercritical CO₂ power cycles are out of scope of the request.

²⁶ Carbon Capture and Storage

increase efficiency, to reduce energy and materials consumption and to prove the technologies at large scale and in different settings are needed.

The Commission provides a wide range of research and development grants in the field of CCU. Furthermore, CCU demonstration projects will be eligible to bid for support from the future Innovation Fund, *inter alia*, as one of the technologies and processes for decarbonisation of energy-intensive industries.

However, CCU still faces a number of technical challenges: advancement of knowledge is essential to improve the economic and environmental feasibility and the potential of the technologies. It includes for instance research in CO₂ catalytic science, novel CO₂ reaction pathways, novel reactor designs and the translation of this research into breakthroughs in processes.

Information on the environmental performance of the technologies is currently limited and scattered. While some studies are available that assess the climate change mitigation potential of CCU applications based on Life Cycle Analysis (LCA), this approach is not coherent with the monitoring and reporting framework that is applied within the large installations that are covered by the Emissions Trading Scheme (EU ETS), which is based on annual monitoring, reporting and verification of emissions from each specific installation at the site of the installation. In addition, the most promising CCU technologies appear to require significant amounts of energy. This means that even in situations where an LCA could potentially capture relevant impacts for a CCU technology, the climate mitigation potential, in particular, would also depend on the availability of low-carbon electricity, the efficiency of the technologies, the greenhouse gas intensity of inputs, how long and stable the CO₂ remains bound in its new form, and what products are replaced. As a result, a LCA can lead to very different results depending on the specific technologies and plants considered.

EU international climate obligations require detailed monitoring and reporting of greenhouse gas emissions. Currently, the EU ETS only provides a derogation from greenhouse gas emissions for CCS involving geological storage in accordance with the CCS Directive²⁷. CCU technologies bind the CO₂ molecule in a multitude of different products for different periods of time. Currently, unless captured carbon dioxide is permanently stored, it is counted as emissions under the ETS Directive, due to the lack of a methodology for accounting for possible CO₂ releases in the future. The absence of such an approach reflects the novelty of the technologies as well as the multitude of different products and end-of-life possibilities.

The economic feasibility of CCU technologies also depends on a number of factors, such as the costs of inputs (CO₂, electricity, catalysts, etc.), technological improvements and the price of products they substitute. CCU technologies like

²⁷ Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide

many innovations offer alternative processes and pathways to produce substitute products in the market, and therefore face commercial challenges in replacing long-established market incumbents.

CCU technologies can provide storage of intermittent renewable energy but the need for such storage is in competition with other storage and grid management solutions and therefore potential in the future is unclear.

Some mineralisation pathways are already competitive (e.g. reacting CO₂ with industrial and municipal solid waste to produce building blocks) but their market potential is limited by the volume of waste or by the need for close-by sources of CO₂ and other raw materials.

The quality and quantity of CO₂ could also be a challenge. CO₂ needs to be captured, concentrated and purified before it can be used at least for some of the processes. This can be energy intensive and costly. However, certain industrial processes offer nearly pure CO₂ and some conversion technologies can use the flue gases without much purification or concentration. The volumes of available CO₂ may not match the needs of utilisation unless clusters of capture, utilisation and storage are developed.

Request to SAM HLG

In this context, the Scientific Advice Mechanism High Level Group (SAM HLG) is asked by the end of April 2018 to provide scientific opinion on the challenges and opportunities of novel carbon capture and utilisation technologies in particular with respect to their climate mitigation potential.

Questions to be addressed by SAM HLG

In this context, SAM High Level Group is asked to provide scientific advice based on existing research on the climate mitigation potential of CCU technologies to inform future policy decisions in this field over the next couple of years, including financial support. In particular, there is a need to ensure that support is limited to technologies that are environmentally safe and provide substantial climate benefits.

- Under what circumstances CCU for production of fuels, chemicals and materials can deliver climate benefits and what are their total climate mitigation potential in the mid- and long-run?

- How can the climate mitigation potential of CO₂ incorporated in products such as fuels, chemicals and materials be accounted for considering that the CO₂ will remain bound for different periods of time and then may be released in the atmosphere?

Further procedures and actors in support of the SAM High Level Group

EU academies and the wider scientific community: The EU academies are a key provider of scientific evidence to the SAM HLG. The relevant EU academies will be asked for their inputs. The engagement of leading scientists will be organised.

The European Commission's Joint Research Centre (JRC) will also provide scientific evidence to the SAM HLG.

Annex 3 - Meeting with Stakeholders

Agenda

**Novel Carbon Capture and Utilisation Technologies (CCU): Research and Climate aspects, Stakeholders meeting,
20th February 2018, Brussels
CDMA Building, rue du Champ de Mars, 21
1050 – Bruxelles**

13:30	Registration and welcome coffee
14:00	Welcome by Elvira Fortunato (Member of Group of Chief Scientific Advisors SAM)
14:05	Tour de table
14:20	Presentation by Johannes Klumpers (Head of Unit, SAM): The European Commission's Scientific Advice Mechanism
14:45	Presentation by Elvira Fortunato: Main elements of the draft Scientific Opinion ' <i>Novel carbon capture and utilisation technologies: research and climate aspects</i> '
15:05	Presentation by Robert Schlögl (chair of the SAPEA Group of Experts) and Marco Mazzotti (co-chair of the SAPEA Group of Experts): ' <i>The SAPEA Evidence Review Report on Novel Carbon Capture and Utilisation Technologies (CCU)</i> '.
15:15	Discussion on issues and questions to be brought up by stakeholders
16:45	Wrap-up of the meeting by Elvira Fortunato (Member of the High-Level Group of Scientific Advisors)
17:00	End

Participants list

The Stakeholder workshop was by invitation only, with the number of participants being limited to around 40 in order to create an ideal working environment for a useful discussion. Participants from Industry, Academia and Civil society organisations included:

Buffet Laura T&E; Cooper John Fuels Europe; Dallemagne Damien CO2 Value Europe; Duic Neven SAPGAM; Fortunato Elvira SAM Group of Chief Scientific Advisors; Gehrisch Wolf Euro-Case; Jungk Gunnar ThyssenKrupp; Kaemmer Sebastian GasNaturally; Kumar Sanjeev Change Partnership; Mazzotti Marco SAPEA CCU Expert Group Vice Chair; Porteron Samy Ramboll; Schoegl Robert SAPEA CCU Expert Group Chair; Vaniterson Rannveig European Climate Foundation; Warren Luke ZEP; Whiriskey Keith BELLONA; Wilmet Sophie CEFIC.

Additional participants from European Institutions included: DG RTD - DG Research and Innovation: SAM Unit: Johannes Klumpers; Maria da Graça Carvalho; Dulce Boavida, Jacques Verraes, Maurizio Salvi (Secretary of the event); Advanced Manufacturing Systems and Biotechnologies Unit: Carmine MARZANO Jürgen TIEDJE; Climate Action and Earth Observation Unit: Andrea TILCHE; DG CLIMA - DG for Climate Action: Nadia Vedrova; DG ENV – DG for Environment: Jesús Alquezar Sabadie.

Summary

The objective of the workshop was to gather views from stakeholders on the matter and to expose stakeholders to some first ideas of SAM, enabling the SAM Group of Chief Scientific Advisors to test the feasibility of its future opinion with policy, industry and civil society stakeholders.

Besides the members of the Group of Chief Scientific Advisors subgroup and the SAM Secretariat, representatives of the following stakeholders (pan European level) were invited to the meeting:

- Business Stakeholders
- Civil Society Stakeholders
- Science Stakeholders
- Policy Stakeholders (observer status): European Commission (DG SG, DG CLIMA, DG GROW, DG ENER, DG MOVE, DG ENV, DG RTD, DG JRC), European Parliament (European Parliamentary Research Service)

Invited participants' were asked to participate following the following instructions:

1. The critiques and inputs from invited participants had to take the form of a reality-check of a possible mass use of CCU across the EU. As such, invitees had to explicitly comment on the feasibility, practicality or applicability, and quantification of a policy design on CCU
2. Invited participants had to voice the main socio economic determinants that should be considered in such an effort.
3. Invited participants had to voice considerations on what not to be forgotten or underestimated for the EU to prepare a policy frame on CCU at pan-European or International level.

Stakeholders meeting

Elvira Fortunato (member of the member of the Group of Chief Scientific Advisors) opened the event and reminded the participants that the main goal of the event is to collect inputs by relevant stakeholders.

Johannes Klumpers (Head of Unit, SAM) reported on the SAM mechanism and the way it operates in the EC.

Elvira Fortunato (member of the member of the Group of Chief Scientific Advisors) presented the Group's draft Opinion. She reported on the SAPEA evidence report and summarised the events organised to prepare the Group's CCU Opinion including the SAPEA expert workshop (25/01/2018).

Marco Mazzotti (co-chair of the SAPEA Group of Experts) reported on the results from the SAPEA report.

Following the above presentations, a debate followed where relevant stakeholders were asked to voice concerns, expectations and signal main elements to consider. The discussed items included, inter alia:

- The cyclical approach to CCU in the short and medium terms transition to a low carbon future (energy and industry);
- CCU in the context of societal services;
- CCU and the European Union energy systems;
- CCU and CO₂ unavoidable emissions (industrial sectors);
- CCU climate mitigation potentials;
- Storage of CO₂ (fuels, chemicals, materials, mineralisation, carbonisation etc.);
- CCU technologies;
- Research and market implications of CCU.

Invited participants were also asked to send comments and contributions to the SAM Secretariat.

The report of the event was published in the SAM CCU page <https://ec.europa.eu/research/sam/index.cfm?pg=ccu>.

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Annex 5 – Glossary

IRL: A systematic measurement of the interfacing of compatible interactions for various technologies and the consistent comparison of the maturity between integration points.

SRL: a function of the individual Technology Readiness Levels (TRL) in a system and their subsequent integration points with other technologies, the Integration Readiness Level (IRL).

TRL: a systematic metric/measurement system that supports assessment of the maturity of a particular technology and the consistent comparison of maturity between different types of technologies

Process CO₂: CO₂ that is emitted as inherent, unavoidable part of the process and which is unrelated to the source of energy (fossil or renewable)

Syngas: Syngas is an abbreviation for synthesis gas, which is a mixture comprising of carbon monoxide, carbon dioxide, and hydrogen.

CAPEX: Capital expenditure - are funds used by a company to acquire, upgrade, and maintain physical assets such as property, industrial buildings, or equipment.

e-fuels: are gaseous and liquid fuels such as hydrogen, methane, synthetic petrol and diesel fuels generated from renewable electricity.

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This Scientific Opinion responds to a request from the European Commission formulated by Commissioner Cañete (Commissioner for Climate Action and Energy) and addresses the climate mitigation potential of the suite of technologies that capture CO₂ from industrial processes or from the air and which convert it into fuels, chemicals and materials, also known as Carbon Capture and Utilisation or CCU.

The rationale behind the study is the need to develop tools and technologies to reduce CO₂ emission to keep global warming during this century well below 2°C. This corresponds to the commitment which the European Union and its Member States took in the context of the 2015 Paris Climate Agreement.

The Opinion draws on the best available scientific and technical evidence from across Europe gathered in an Evidence Review Report produced by SAPEA, an independent Horizon-2020 funded consortium of European scientific academy networks.

The Opinion concludes that for CCU to contribute to climate change mitigation, the energy used in CO₂ conversion must be of low carbon origin. In addition, and because the converted carbon may be held in the product for a variable amount of time and not always permanently, assessment of the climate mitigation potential of the technologies also depends on a life cycle assessment (LCA) approach which takes into account the fate of carbon once released from the product.

Moreover, the Opinion recommends that European Commission develops a regulatory and investment framework to enable the deployment of CCU technologies; and a methodology to allow the calculation of the climate mitigation potential of CCU applications, which is also rolled out beyond the EU.

Studies and reports

