European Commission

Identification and analysis of promising carbon capture and utilisation technologies, including their regulatory aspects

Final report

Written by Ramboll, the Institute for Advanced Sustainability Studies, CESR – Center for Environmental Systems Research at the University of Kassel, CE Delft, and IOM Law

January – 2019

EUROPEAN COMMISSION

Directorate-General for Climate Action

Directorate C – Climate strategy, Governance and Emissions from Non-trading Sectors

Unit C3 – Land Use and Finance for Innovation

Contact: Maria Velkova

E-mail: Maria.Velkova@ec.europa.eu

European Commission

B-1049 Brussels

Identification and analysis of promising carbon capture and utilisation technologies, including their regulatory aspects

Final report

Written by:

Ramboll: *Samy Porteron, Emiel de Bruijne, Xavier Le Den, Ferdinand Zotz*

Institute for Advanced Sustainability Studies: *Barbara Olfe-Kräutlein, Annika Marxen, Henriette Naims*

Universität Kassel Center for Environmental Systems Research: *Sebastian Turnau, Stefan Bringezu, Simon Kaiser*

IOM Law: *Ingvild Ombudstvedt, Ada Gimnes Jarøy. Maria Ellingsen Gran*

CE Delft: *Sander de Bruyn, Diederik Jaspers*

Table of Contents

Table of Figures

Table of abbreviations

AM Approved Methodologies

AVR Accreditation and Verification Regulation

BAT Best Available Techniques

BisA-PC Polycarbonate

BREFs Emerging technique in existing and/or future BAT reference documents

CAPEX Capital costs

CA-S Underwater compressed air energy storage

CCS Carbon Capture and Storage

CCU Carbon Capture and Utilisation

CDM Clean Development Mechanism

CDU Carbon Dioxide Utilisation

CE Circular Economy

CEAP Circular Economy Action Plan

CED Cumulative Energy Demand

CER Certified Emission Reduction units

CF Cohesion Funds

CH_4 Methane

CLP Regulation for the classification, labelling and packaging of substances and mixtures

CJEU European Court of Justice

CO_2 Carbon dioxide

CO_2-EHR Enhanced hydrocarbon recovery

COPs Community Offset Projects

CPR Construction Products Regulation

CR Carbon Recycling

DAC Direct Air Capture

DEHST German Emissions Trading Authority

DMC Dimethyl carbonate

DME Dimethyl ether

DOPs Community Offset Projects

DVGW German Technical and Scientific Association for Gas and Water

EED Energy Efficiency Directive

EFSI European Fund for Strategic Investments

EHR Enhanced Hydrocarbon Recovery

EIA Environmental Impact Assessment

ELD Environmental Liability Directive

E-PRTR European Pollutant Release and Transfer Register

ERDF European Regional Development Funds

ESD Effort Sharing Decision

ESIF European Structural and Investment Funds

ESR Effort Sharing Regulation

EU ETS EU Emissions Trading System

EWD Extractive Waste Directive

FQD Fuel Quality Directive

GHG Greenhouse Gas

GHS United Nations Globally Harmonised System

GWI Global Warming Impact

GWP Groundwater Protection Commission Directive

H2020 Horizon 2020

H_2-S Hydrogen

HFCs Hydrofluorocarbons

IED Industrial Emissions Directive

IPCC Intergovernmental Panel on Climate Change

LCA Life-Cycle Assessment

LCAI Life-Cycle Assessment Inventory

LCC Life-Cycle Costing

LiI-B Lithium-ion battery

LNG Liquefied Natural Gas

LPG Liquefied Petroleum Gas

LULUCF Land use and forestry proposal for 2021–2030

MEA Monoethanolamine

MRR Monitoring and Reporting Regulation

MRV Monitoring, Reporting, Verification regulation

MTO Methanol-to-olefins

N_2O Nitrous oxide

NaS-B Sodium-sulphur battery

NDC Nationally Determined Contribution

NER300 New Entrants Reserve 300

NPV Net Present Value

OME1 Oxymethylene ether

OPEX Operational costs

PbA-B Lead-acid battery

PCC Precipitated Calcium Carbonate

PE Polyethylene

PFCs Perfluorocarbons

POM Polyoxymethylene

POP Persistent Organic Pollutants

PP Polypropylene

PtX Power-to-X

PU Polyols for Polyurethane

REACH European Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals

RED Renewable Energy Directive

RFCS The Research for Coal and Steel Fund

RMI Raw Material Input

SDGs United Nations Sustainable Development Goals

SEA Strategic Environmental Assessment

SET Strategic Energy Technology Plan

SF_6 Sulphur hexafluoride

SL-B Second-Life Battery

SNG-S Synthetic Natural Gas

SVHC Substances of Very High Concern

TBME Methyl tert-butyl ether

TEA Techno-economic assessment

TMR Total Material Requirement

TRL Technical Readiness Levels

UNFCCC United Nations Framework Convention on Climate Change

VRF-B Vanadium redox flow battery

WFD Waste Framework Directive

WIPP Waste Incineration Power Plant

Executive Summary

1. Context

The utilisation of carbon dioxide in diverse production processes is referred to as Carbon Capture and Utilisation (CCU). This refers to technologies and processes, which either directly use CO_2 such as in soft drinks or greenhouses or use it as a working fluid or solvent such as for enhanced hydrocarbon recovery (EHR); or use CO_2 as a feedstock and convert it into value-added products such as polymers, minerals, chemicals and synthetic fuels.

The latter *conversion* CCU technologies are the focus of this study. Conversion CCU technologies currently stand at various Technology Readiness Levels (TRL).[1] Many of these technologies are currently still in development and are not commercialised. However a few have been scaled up and products have already reached markets where they can be used to replace products conventionally produced from fossil or bio-based sources of carbon. This study focuses on conversion CCU technologies which are expected to be ready for large-scale demonstration in the next decade. The study therefore excludes *direct use* CCU technologies and it also excludes technologies which are currently at early TRL or that are already in commercial use, such as urea.

Despite a common first step to capture CO_2 from industrial emissions or directly from the air, CCU also differs fundamentally from so-called 'Carbon Capture and Storage' (CCS) technologies. While CCS, as 'end of pipe' technologies, aspire to the permanent underground storage of CO_2, CCU aims at economically utilising CO_2 as an alternative source of carbon, with the perspective of at least partly closing industrial carbon cycles. CCS technologies were therefore also not in the scope of this study.

CCU could offer a promising avenue for creating a circular economy, industrial innovation and decarbonisation, as well as competitiveness of energy intensive industries. However, to realise their potential CCU technologies require various forms of policy support in order to be economically viable and better integrate CCU into the broader economy. The European Union already provides a wide range of research and development grants in the field of CCU. For instance, CCU demonstration projects are eligible to bid for support in the EU ETS Innovation Fund under the EU Emissions Trading System (EU ETS), as one of the technologies and processes for decarbonisation of energy-intensive industries.

While CCU offers to close carbon cycles, most CCU technologies require significant amounts of energy. To this day, their climate benefits (net carbon emission reduction) are not clear to public, industry and policy-makers alike and need to be thoroughly calculated for each specific application. The climate mitigation potential of CCU technologies is dependent on the carbon intensity of the electricity used for the processes, the efficiency of the technologies, the greenhouse gas (GHG) intensity of other inputs, how long the CO_2 stays in its new form, and which products or fuels they replace. As a result, life cycle analysis of CCU applications can lead to very different results depending on the specific technologies considered. The economic feasibility of CCU technologies also depends on a number of factors, such as the costs of inputs (CO_2, electricity, catalysts, etc.), technological improvements and the price of alternatives.

[1] For the European Commission definition of Technology Readiness Levels, see https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

The context of high concerns over the impacts of climate change from anthropogenic GHG emissions raises the question of the potential contribution of CCU to climate action and requires clarity over the methods to measure the actual climate benefits of CCU technologies. Without such clarity over methods, it will not be possible to develop the appropriate policy framework including funding and legislation to support promising CCU technologies while protecting the environmental integrity of the EU policy framework.

2. Objectives of the study and methodological approach

This study was initiated by the European Commission Directorate-General for Climate Action, and attributed to a team of experts from Ramboll, the Institute for Advanced Sustainability Studies, Universität Kassel Center for Environmental Systems Research, IOM Law, and CE Delft. The study's objectives are to build a better understanding of novel CCU technologies with three main sub-objectives:

1. to assess the readiness and map the roll out of different CCU technologies in order to clarify which types of technologies are viable for support, including from the planned Innovation Fund under the EU ETS;
2. to examine the EU regulatory set up related to the technologies concerned and assess whether specific provisions are necessary to reflect the contribution by these innovative technologies to climate mitigation while preserving the environmental integrity of the relevant legislation; and
3. to engage with stakeholders for better understanding of the technologies and the legislative setup.

To achieve its objectives, the study team conducted a review of the literature on CCU; a web search on the status of existing technologies; a review of relevant legislation; as well as stakeholder consultations in the form of a survey, interviews, two stakeholder workshops and an open event. The study draws from existing knowledge and research, and represents a state-of-the-art review of the current technological and policy status of CCU in Europe. Despite the important data collection and analysis conducted in this report, the ongoing development of the technologies and of the policy framework mean that the study's conclusions may not capture future pathways of the sector and policy framework.

3. Structure of the report

The main report is structured in two main tasks:

Task 1 is a technology assessment which consists of the identification of a longlist of CCU technologies and related products, reduced via a multiple-criteria analytical method to a shorter list of 15 promising CCU products from the four main product categories (polymers, minerals, chemicals and synthetic fuels). This is followed by an economic, climate and energy assessment of the shortlisted CCU products including a cradle-to-gate life-cycle analysis (LCA) of five CCU products. Finally, an analysis of the market barriers, impacts and opportunities for the 15 shortlisted products is presented.

Task 2 is a regulatory assessment which begins with an analysis of the broad current regulatory framework including potential regulatory issues related to the development of CCU, followed by a development of relevant policy options to address regulatory issues and maintain the environmental integrity of the EU policy framework. Finally, an initial assessment of the potential impacts of the policy options is given.

4. Findings of the study

4.1 Summary of key findings

Before addressing the more detailed findings of the study, this chapter underlines a number of key findings regarding the environmental impact of CCU which are pivotal in understanding the implications of their deployment and their relevance for European policy objectives.

The climate mitigation potential of CCU processes is limited by the availability of renewable energy. In order to achieve lower net carbon dioxide emissions compared to conventional products made from fossil- or bio-based feedstocks, CCU products require the use of renewable energy sources. Using grid energy in particular would not be beneficial from a climate mitigation perspective: taking Germany as reference, the percentage of renewable electricity would have to be a minimum of 86% in order to break-even in net carbon emissions between CO_2-based and conventional fossil-based products.

The climate mitigation potential of CCU products is dependent on the substitution of similar products on the market made from fossil- or bio-based feedstocks, otherwise CCU products would simply create a rebound effect with more material use and CO_2 emissions. Some of the main barriers to this substitution are the competition with fossil products (price) and the related lack of demand for CCU products.

CCU is a relevant solution for the creation of a circular economy, the replacement of fossil fuels and for reducing the reliance on fossil imports. However, CCU technologies will not allow society to fully break away from its reliance on carbon. Therefore, CCU should be considered as a relevant solution where carbon is necessary, such as in the chemical industry. In sectors where hydrocarbons can be replaced by low-carbon technologies such as renewable electricity and hydrogen in transport (i.e. e-mobility, hydrogen fuel cell), the production of CCU chemicals and fuels would have to compete for the supply of renewable electricity or hydrogen, yet CCU would present much lower energy efficiency rates than if these alternatives were used directly as power sources. Another benefit of CCU chemicals and fuels is their potential to store renewable energy which would otherwise be curtailed, assuming abundance of cheap renewable energy. Fuels and chemicals from carbon dioxide can support the transition away from fossil fuels until possible alternative and lower-carbon materials, infrastructure and systems are deployed, such as hydrogen transport fuelling stations and electric vehicles.

Mineralisation technologies which transform CO_2 and other input materials into a mineral product (such as calcium carbonate or serpentine) differ in terms of CO_2 emissions based on whether additional mining is needed to source the input materials. For most mineralisation technologies, adequate LCA data to draw conclusions on the global warming impact of these technologies is not publicly available, however the study allowed to identify some climate-beneficial routes.

Having made these considerations, and considering EU climate, energy and resource-efficiency objectives, the financing of CCU technologies can potentially lead to the suboptimal allocation of public and private investments if their wider implications are not considered. It is thus crucial that each CCU project proves its environmental benefits with a robust LCA.

4.2 Identification of 'promising' CCU technologies

In order to allocate European funding efficiently while at the same time positively contributing to EU environmental objectives, it is necessary to identify and assess 'promising' technology applications at a sufficiently mature technological development stage, so that they can be expected to be ready for demonstration at pre-commercial scale within the next decade (up to 2030) and possibly provide an environmental advantage.

A longlist of 130 CCU application options stating their respective Technological Readiness Level (TRL) was thus compiled including materials, minerals, chemicals and fuels. Since products can have different uses and some belong to several categories. From the longlist, 'promising' CCU routes were shortlisted based on a multiple-criteria analysis including: time to commercialisation, financial gap for large-scale demonstration projects, technical advancements necessary, replication potential, financial indicators, product price, total EU production and import volume, availability of LCA data, potential annual CO_2-binding volume, product usage and retention times.

The 15 most promising CCU routes[2] shortlisted include: fuels and base chemicals (ethanol, methane (biological), methane (chemical hydrogenative), methanol, oxymethylene ether (OME1)), chemicals (ethylene; propylene), intended for the production of polymers (polyethylene (PE)), polyoxymethylene (POM), polypropylene (PP), polycarbonate (BisA-PC), polyols for polyurethane (PU) foams production) and minerals (calcium carbonate and sodium carbonate).

The assessment based on the aforementioned criteria is a viable approach for identifying promising CCU products and technologies. The theoretical total annual CO_2 binding volume of the 15 shortlisted products amounts to 1928 Mt CO_2 per year. This estimate is based on the binding potential of the specific chemical formula and a best-case market scenario (if total European production and imports were produced via the CCU route in an ideal system and the reactions were stoichiometric) for each selected product. Still, the limited data availability does not allow a definitive statement on economic market size of the products. What is more, economic, commercial and technical data is highly technology-specific and therefore project-specific. Even if data is available for one single project, it cannot be generalised for all products since economic and environmental data also depend on location, CO_2 input sources, energy supply, etc.

It must be emphasised that although this method is a viable traffic light approach, the data compiled are estimates in theoretical 'best case' scenarios. In order to make a definite statement on what products and technologies have the largest potential in terms of total emission reductions and what is the potential volume of emission reductions/avoidance, a comprehensive LCA of each full process as well as a detailed market analysis have to be conducted. The source of energy should also be considered, which can be done only on a project by project basis.

A standardized LCA for CCU products, minimum GHG savings and minimum resource efficiency requirements compared to conventional technologies would be a necessary precondition for a possible award under the Innovation Fund and needs to be undertaken for each application individually. The ILCD Handbook General guide on LCA (2010) and several other publications (Jung, von der Assen, & Bardow, 2013; von der Assen et al., 2013; von der Assen, Lorente Lafuente, Peters, & Bardow, 2015) and initiatives[3] are already providing guidance or are preparing proposals for a standardisation of LCA for CCU.

As for other funding options, the current eligibility conditions for financing programmes and instruments under the multi-annual financial framework for the period 2014-2020 in principle offer possibilities for financing CCU projects. These opportunities can be leveraged for CCU projects where these can potentially deliver benefits with regards to *inter alia* innovation, climate action, renewable energy, energy and resource efficiency, in line with the respective objectives of each programme.

4.3 Economic assessment

As CCU applications differ widely and will be confronted with specific market situations, this report analyses the major economic preconditions necessary for the implementation of all CCU

[2] A CCU route, as described above, names a certain chemical reaction that results in a chemical product.

[3] E.g.: https://www.iass-potsdam.de/de/forschung/development-guidelines-techno-economic-analysis-tea-co2-conversion-processes

technologies. The economics of CCU technologies are determined mainly by the sources of CO_2, its concentration and purity and the availability and pricing of renewable energy. However, other factors will play important roles such as the availability of CO_2 transport infrastructure or proximity between CO_2 sources and industries capable/interested in investing in novel technologies.

Many different CO_2 sources are suitable for CCU applications. The ideal source will be determined for each application specifically via the purity of the CO_2 that is required, the proximity of the source, and price. Several industrial emitters are suitable as sources of high purity CO_2, for example the production of bioethanol or of hydrogen or, at a higher capture cost, ethylene production or cement plants.

The ecological feasibility of many technological options, particularly air capture and power-to-X (PtX), relies on the availability of competitively priced renewable energy. The EU energy scenarios for 2030 and 2050 project a growing share of renewable energy in the energy mix. This development might foster the ecological feasibility of CCU technologies if more renewable energy is produced than required by the energy market. Furthermore, rising oil prices will make CCU technologies as replacement options more attractive. CCU technologies themselves can foster advancement towards an optimized usage of renewable energies by providing options for energy storage.

Previous studies showed that using CO_2 as a raw material for chemical synthesis may provide an opportunity for achieving greenhouse gas savings and a low-carbon economy. Nevertheless, it is not clear whether CCU benefits the environment in terms of resource efficiency.

4.4 Climate and energy assessment: life-cycle analysis methodology and results

LCA was conducted for the production of methane and methanol, as basic chemicals, and synthesis gas as intermediate, and derived polyoxymethylene, polyethylene and polypropylene as polymers.

Comparative LCA has been conducted on a cradle-to-gate basis, comparing CCU products with their conventional substitutes. The CCU products are compared by calculating the output-oriented indicator *global warming impact* (GWI), the resource-based indicators *raw material input* (RMI) and *total material requirement* (TMR), the *cumulative energy demand* (CED), and the water input.

In terms of carbon sources, this report analyses the capturing of CO_2 from air, raw biogas, cement plants, lignite-fired power and municipal waste incineration plants. Wind power serves as an energy source for hydrogen production. Data was derived from both industrial processes and process simulations. Different scenarios were evaluated to find favourable transport routes, first inter-sectoral use analysis or the break-even share of renewable electricity to achieve environmental impact reduction. Individual energy demand for capturing CO_2 from different sources is considered.

The results indicate that for methane and methanol production and subsequent synthesis stages, using cement kilns, waste incinerators and raw biogas as CO_2-sources could be a promising option for saving GHG emissions. The beneficial use of point sources depends strongly on local conditions such as the availability of waste heat. Direct air capture shows the highest energy demand for capturing CO_2 and hence a large potential for waste heat utilisation in industrial symbiosis, but is less preferable than industrial point sources if no waste heat is available.

The results demonstrate that the CO_2-based process chains analysed can reduce the amount of GHG emissions in comparison to conventional processes. At the same time the CO_2-based process chains present a trade-off in that they require an increased amount of (abiotic) resources. The decision on whether to recycle CO_2 into hydrocarbons depends largely on the source and amount of energy used to produce hydrogen. The evaluated routes can only be environmentally beneficial if a large share of renewable or waste energy is used for the production.

A CO_2 mitigation effect by substitution is independent from the durability of products and so-called 'retention time' of carbon given the current product use, consumption and disposal patterns. This is because in most cases a CCU product replaces a conventional product identical in chemical composition and physical condition, and both are also used, recycled and disposed of in the same way. If the type of final product consumed does not change, the existing pattern of short and long-lived products will remain and the only mitigation effect will relate to net emission reduction during the production phase.

Having made these findings, we draw two key conclusions:

- When considering the same product patterns, the retention time for carbon in CCU products versus conventional (fossil- or bio-based) products remain the same and thus is an irrelevant metric for measuring the CO_2 balance.
- From a climate mitigation perspective, the benefit of CCU processes depends on the net GHG emission balance of the process from cradle-to-gate, for all types of products (minerals, polymers, fuels and chemicals) under the condition that conventional products are replaced.

4.5 Market barriers, opportunities and impacts of CCU deployment

From today's point of view, CCU technologies are unlikely to create completely novel products, as technology developers largely try to fit new products to existing markets. CO_2-based products need to be of comparable (or improved) quality and competitively priced in order to successfully permeate these markets. Due to the early stage of development of most CCU technologies, CO_2-based production capacity is likely to remain marginal over the next ten years.

CCU technologies have the potential to contribute to various environmental policy aspects. CCU could be a potential way to stimulate emission reductions – i.e. investments in CCU technologies could be supported by deriving an economic value from the CO_2 products and hence incentivise the capture of CO_2 emissions. The current low prices for fossil resources acts as an obstacle to the competitiveness of CO_2-based hydrocarbons and further development of CCU technology.

Without regulatory support, it will not be possible for certain technologies to continue competing with cheap fossil materials. Although some technologies may be sensible from an ecological perspective, CCU technologies' environmental benefits are not currently well recognised in policy frameworks. A rise in prices for fossil resources and/or increased availability of renewable electricity and other forms of energy from renewable resources at as low cost as possible could support the implementation of such technologies. Moreover, further barriers are specific to each CCU application. In particular, all fuel-related products will strongly depend on policy support, since from today's point of view, they will not be able to compete with conventional fuels due to their pricing.

Potential synergies could be enabled if CCU technologies are implemented via cross-sectoral collaborations as "industrial symbiosis". This approach can make them applicable and ecologically worthwhile as flows of production inputs and outputs are shared among production units. Specific in the context of CCU, building synergetic ecosystems has been identified as being useful in overcoming resource shortcomings of individual players (Kant, 2017).

Potential users of captured CO_2 can be a diverse range of actors. The local availability of renewable energy which can be decisive for making CCU ecologically worthwhile can be secured by providing proximity with energy producing facilities (e.g. wind or solar energy) or industrial processes that offer waste heat. Another unit involved could provide the electrolysis if necessary.

Consequently, the identification of opportunities for industrial symbiosis, clusters of industrial parties and the set-up of new value chains should be pursued and fostered by policy makers, research funding schemes and researchers but especially developers. The specific potential for industrial symbiosis will be project- and technology-specific and no general quantitative conclusions can be drawn at this point.

Large-scale CCU might influence the industrial production in certain regions of Europe. Depending on technology specific contributions, new procedures and plants could lead to reductions of use of fossil raw materials in the long term, particularly in the chemical industry. Also, the implementation of CCU technologies could lead to a new and potentially growing demand for renewable energy.

It is assumed that CCU can contribute to a modernization of the industry and also has the potential to create economic growth (Wilson et al., 2015). Positive effects on produced output and/or GDP growth cannot be clarified today and will depend on several factors. Detrimental rebound effects due to increased amounts of products and waste, also need to be taken into account.

As an effect on foreign trade, the potentially reduced consumption of raw materials could lead to a reduction in dependency on the import of fossil resources in the long term. The new types of CCU processes which could lead to valuable technical know-how and numerous patents, could also imply a technological advantage in international competition. This could have a positive effect on the export statistics if CCU technologies and products from Europe were to be demanded and offered on international markets.

Regarding cohesion within the EU, the potential effects of the implementation of CCU are difficult to foresee. Local solutions in industrial symbiosis might advance the concentration of production factors and thus hamper cohesion. On the other hand CCU with, for example direct air capture technologies, could in the long term also allow for local technological solutions for regions that are more remote and not yet industrialized.

One potential economic risk could be the suboptimal allocation of public and private investments in CCU. Significant losses could occur in specific sectors if CCU processes were coupled with certain conventional industrial plants set to be phased out for economic or environmental reasons. Projects should be considered according to their strategic alignment with European targets. Looking at the anticipated development of power generation in the EU until 2050, it becomes evident that the implementation of CCU throughout the EU member states needs to consider the undesirable lock-in effects of conventional electricity generation infrastructures, and the respective strategies for base-load electricity supply and plant running times that are required to allow for cost efficiency. In particular, using fossil power plants as CO_2 sources may delay the roll-out of more environmentally beneficial power generation.

An overall positive effect in the area of investment financing could be the founding of businesses associated with CCU. Entrepreneurship is seen as essential for Europe’s economic growth and the development of jobs, markets and skills (European Commission, 2018). However, several barriers for new CCU ventures have been highlighted, such as access to institutional investors which is seen to be crucial for scaling-up and developing first-of-a-kind projects. Due to the diversity in CCU technologies and geographic contexts, tailored support solutions are recommended (Kant, 2017). Regulatory conditions should also be reconsidered in relation to enabling investment security and reducing relevant potential risks for investors.

4.6 Societal barriers to CCU deployment

Current studies on the perception of CCU technologies do not indicate strong reservations against them. Rather, the technologies and their effects tend to be assessed in a positive manner. In order to foster the public acceptance of CCU technologies, current research suggests a clear distinction between CCU and CCS, to integrate LCA results in communication activities, and to limit communication activities about the mitigation potential of CCU technologies to realistic scenarios in order to avoid exaggerated expectations.

Overall, the societal barriers in implementing CCU technologies as well as the opportunities they offer are diverse and technology-specific to a large extent. Some of them can be influenced by policy measures, others depend on the market, technological advances or other developments that cannot yet be foreseen. Possible policy measures should take possible effects into account and should be designed accordingly in line with EU policies, also recognising that it might be necessary to consider policy measures applicable to specific CCU technologies only.

4.7 Assessment of the regulatory framework

In order to allow for a deployment of novel and promising CCU technologies, this study examines the EU regulatory set up related to these innovative technologies and assesses whether specific provisions are necessary to reflect their contribution to climate mitigation, all the while preserving the environmental integrity of the EU legislative framework.

For that purpose, the study includes a systematic mapping and review of legislation which affects the technologies shortlisted. The mapping identified more than fifteen pieces of legislation with relevance to the shortlisted technologies.[4] The regulatory assessment is structured by the thematic policy frameworks to which they belong. It is important to note that the assessment was performed without a full understanding of the entire scope of potential environmental impacts of the shortlisted technologies and CCU technologies in general and is limited by the state of current knowledge.

Climate and energy policy framework

The 2030 climate and energy targets set three targets to be achieved by 2030: 40% GHG emission reduction, 32% increase in the share of renewable energy, and 32.5% improvement in energy efficiency relative to 2005 levels and for the economy as a whole.

The GHG emission target is addressed by the Emission Trading System Directive (No EC/410/2018) or ETS Directive on the one hand, targeting sectors which include power/heat generation and industrial production including of metals, cement, lime, glass, paper, etc.; and the Effort Sharing Decision (No. 406/2009) and recent Effort Sharing Regulation (No 842/2018) on the other hand, targeting the transport, buildings, agriculture and waste sectors. These targets include a contribution from sectors covered by the effort sharing legislation of 10% by 2020 and 30% by 2030, compared to 2005 levels. Furthermore, the target contribution from installations covered by the EU ETS is 21% by 2020 and 43% by 2030.

The renewable energy target is addressed by the Renewable Energy Directive (No 2009/28/EC) or RED and its recast the RED II (Directive (EU) 2018/2001[5]. The new targeted share of renewable energy consumption of the total energy mix is at least 32% by 2030.[6]

[4] In total, the study reviews twenty-five legislative texts.

[5] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&qid=1546953252892&from=EN

[6] http://europa.eu/rapid/press-release_STATEMENT-18-4155_en.htm

The energy efficiency target is addressed by the Energy Efficiency Directive (No 2018/2002/EU) or EED. The energy efficiency improvement target is at least 32.5% with an upward revision clause by 2023.[7]

Key to upholding the integrity of this framework is to ensure that a coherent GHG emission accounting system is in place that avoids the risk of double counting. In particular, emissions which are saved in one sector (e.g. industrial emissions) should not be counted again as saved in another sector (e.g. transport).[8] However, CCU processes require the use of a GHG accounting approach that differs from the one prescribed by the existing EU mechanisms.

The issue of carbon emissions avoided from the replacement of fossil or bio-based feedstocks is not well accommodated by the current design of the EU ETS, which only considers avoided emissions within installations. The ETS therefore neither currently assumes upstream CO_2 savings nor the comparative LCA approach used in this study, where a fossil or bio-based carbon feedstock in a conventional production process is substituted with recycled carbon in a CCU production process. This means that currently CO_2 avoided by the substitution of a conventional process and fossil or bio-based carbon feedstock cannot be used to justify emissions avoided nor to justify exemptions from having to surrender EU ETS allowances. The ETS does however recognise the specific case of the transfer of waste gases and the transfer of inherent carbon dioxide between ETS installations.

This understanding poses problems for the implementation of the judgement and opinion of the European Court of Justice (CJEU) expressed in January 2017 regarding the case of Schaefer Kalk GmbH & Co. KG v Bundesrepublik Deutschland. This judgement ruled that the European Commission and Member States' competent authorities are required to recognise the emissions avoided in the production of precipitated calcium carbonate (PCC). Some uses of the product PCC can lead to permanent storage of carbon, however other forms of CCU processes leading to temporary storage pose a risk of 'internal carbon leakage', where carbon is released outside of EU accounting systems, for instance if it is burned outside a reporting installation. The carbon may also be reported as captured in an ETS installation but re-emitted in a non-ETS sector (under Effort Sharing) with different pricing and target mechanisms. Recognising CCU as a carbon reduction technique within the EU ETS would shift the burden from industrial installations and onto sectors addressed under Effort Sharing legislation, and potentially compromise the overall GHG target of the EU. Despite arguments made in the court judgement and opinion that the current MRV system should in principle enable the tracking of carbon flows, we conclude that these arguments do not allow for addressing this risk due to the complexity and cost of MRV for such an approach.

A key difference between the ETS and the Effort Sharing legislation is that the ETS has a built-in market incentive mechanism in the form of the carbon market that it creates, wherein installations in ETS sectors only need to purchase and surrender allowances equivalent to their levels of emissions, and can build competitive advantage the more carbon-efficient they are. By contrast, Effort Sharing legislation relies on other policies in its sectors to provide market incentives, such as the RED II for transport, described further in the next paragraph.

While CCU minerals may be easier to accommodate under the ETS due to the lower risk of internal carbon leakage, CCU fuels face high risks of internal carbon leakage as they move from industry into the transport sector. However, CCU fuels may be incentivised in the future under the RED II as 14 % of the transport fuels in all EU countries should come from renewable sources by 2030. This can include recycled carbon fuels or renewable fuels of non-biological

[7] http://europa.eu/rapid/press-release_STATEMENT-18-3997_en.htm

[8] Christensen, A. and Petrenko, C. (2017). CO2-Based Synthetic Fuel: Assessment of Potential European Capacity and Environmental Performance.

origin, and means that ETS incentives for CCU fuels may not be necessary for their deployment. The fuels can now count towards Member States' renewable energy targets so long as they can be proven to be produced from renewable energy, with specific criteria under which the energy has been produced and contributed to the CCU process. While the target share of renewable fuels in the transport sector is an incentive, the criteria for achieving the status of being 'of renewable origin' can be difficult to meet.

As this study's technology assessment shows, many of the CCU products demand intensive energy usage to be produced. The achievement of the objectives of the EED (20% energy efficiency gains in 2020, and improvements beyond 2020) may therefore be challenged by the shortlisted CCU technologies. Although this does not represent a direct hurdle to the deployment of CCU technologies, it may imply that Member States will be reluctant to support large scale deployment of such technologies or implementing policies to support them, or to approve permit application and provide funding to further technology development. However, the consideration of early action and potential for energy storage may weigh positively in the national assessments.

Waste and circular economy policy framework

A key issue for EU waste and circular economy policy is the closing of the material loop via the recycling and reuse of waste, overall reducing the amount of waste discarded (landfilled or burned) and impacting human health as well as the air, water and soil. This issue is intended to be addressed by the EU Action Plan for a Circular Economy (COM(2015) 614 final) or CEAP, the European Strategy for Plastics in a Circular Economy (COM(2018) 28 final), and the Waste Framework Directive (2008/98/EC and EU 2018/851) or WFD.

These policies are closely interrelated as they address the end-of-life of products and suggest the approach to considering waste as a new product. Currently, the policy framework presents some barriers to the marketing and free movement within the EU market of products containing potentially hazardous substances due to different national interpretations of the risk. The varying application of the end-of-waste criteria is a broader issue which affects more secondary raw materials and recycled products. The European Commission has acknowledged the importance of arriving at a more harmonized application of the end-of-waste criteria in its Circular Economy Action Plan and in the new Waste Framework Directive (EU 2018/851).

Furthermore, missing incentives exist for closing the carbon loop, particularly in the recycling of plastics (polymers).

Products and labelling policy framework

Legislation on the design, environmental impact and labelling of products is contained in the Construction Products Regulation (No 305/2011) or CPR, the Ecodesign Directive (No 2009/125/EC), and Regulation No 1272/2008 on the classification, labelling and packaging of substances and mixtures. This legislation is closely linked to the waste and circular economy policy framework as the product policy framework addresses the beginning-of-life of products while waste legislation addresses end-of-life, therefore together comprising the circular approach. Furthermore, these instruments need to be recognized as a coordinated part of the EU's aim to substitute hazardous substances with safer substances, wherever technically feasible.

Overall, this policy framework has not been identified as posing significant barriers to the development of CCU in general. A potential hurdle has however been observed for certain technologies producing concrete block aggregates from waste and which can be addressed under this framework.

Although the ecolabeling provided for in the framework might potentially have some benefits for CCU technologies in relation to the end users, the current status is that the maturity and characteristics of the CCU technologies as a whole are too unclear and diverse to establish a general effect on CCU.

Other policy frameworks

The study also assessed policies under the EU environmental pollution policy framework, which aims to protect the health and well-being of EU citizens by preventing and reducing risks of pollution from industrial activities; the environmental risk policy framework, which provides instruments for security measures and financial liability for the prevention and mitigation of environmental damages and accidents; and policies from the environmental impact assessment policy framework, which requires impact assessments for the evaluation of environmental implications of plans and projects at a level prior to decision making. Overall, these policy frameworks have not been identified as posing barriers to the development of CCU.

Financing programmes and instruments

EU financing programmes and instruments can or already do finance CCU. These are the Framework Programme for Research and Innovation (Horizon 2020), the Research for Coal and Steel Fund (RCSF), the LIFE Climate Action sub-programme, the European Fund for Strategic Investments (EFSI), and the European Structural and Investment Funds (ESIF) composed of the European Regional Development Funds (ERDF) and Cohesion Funds (CF).

EU financing programmes and instruments' resources have so far been mainly targeted at research and development projects for fuels, less so at the scaling up of technologies due to their known low TRL. Other technologies involving the production of minerals, chemicals and polymers have been less supported.

4.8 Developing policy options

Policy options are developed for addressing barriers or gaps identified in the legislation analysed previously. Prior to developing options, key principles for developing sound policy for CCU are identified:

- **Principle 1:** Maintain the integrity of the EU environmental policy framework, particularly with regard to the risk of double counting under energy and climate accounting frameworks.
- **Principle 2:** Avoid technological lock-in effects and account for negative impacts on other environmentally promising technologies, where the phase-out of polluting technologies and replacement by innovative and less polluting alternatives is prevented due to perverse incentives.
- **Principle 3:** Encourage resource efficiency in Europe by replacing less environmentally beneficial conventional production capacity with more beneficial CCU production processes, effectively replacing conventional products with CCU products on markets.
- **Principle 4:** Continue to ensure the technology neutrality of the EU policy framework.
- **Principle 5:** Acknowledge the purpose of most CCU technologies as carbon recycling processes replacing fossil or bio-based production processes, rather than being carbon storage technologies.
- **Principle 6:** Separate incentives to reduce CO_2-intensity of industrial activities (EU ETS) and incentives to recycle CO_2 (circular economy) in acknowledgement of CCU's higher potential for improving circular material flows rather than mitigating climate change.

What is more, several recommendations could be derived from the analysis of literature and stakeholder consultations.

- **Recommendation 1:** Standardised LCA methodologies should be adopted for determining the net CO_2 balance of different CCU products and to inform the implementation of EU policies and EU financing programmes (particularly the RED, Horizon 2020, the Innovation Fund, and other financing programmes).[9]
- **Recommendation 2:** Decisions for supporting specific projects should continue to be made on the basis of specific assessments using above-mentioned standardised or accepted LCA methodologies, due to the fact that results from environmental performance assessments are project-specific.
- **Recommendation 3:** Co-operation between sectors and projects should be encouraged in order to exchange knowledge and share resources, and to facilitate industrial clustering and industrial symbiosis.
- **Recommendation 4:** Foreign diplomatic and policy efforts should be pursued with regards to harmonisation between the ETS and existing or developing national or regional carbon trading schemes, in order to create a level playing field for low-carbon and more expensive products coming from EU industries.
- **Recommendation 5:** CCU should be clearly defined in EU legislation and communications as a carbon-recycling (rather than storage) technology to avoid confusion with CCS, and communication should be clear with regards to the environmental performance of CCU technologies.
- **Recommendation 6:** Where perceived barriers to new technologies subsist, Innovation Deals[10] should be used as an innovation support instrument to guide a stakeholder-led assessment process.

Following these general principles and recommendations, the study offers a definition and discussion of policy options. The policy options together comprise four sets of possible approaches or packages of measures. Note that a quantitative analysis could not be performed in analysing the options.

The EU ETS approach focuses on altering the functioning of the ETS to accommodate for CCU. A long-term option consists in proposing fundamental changes to accounting for GHG emissions avoided in CCU projects, allowing for an accounting approach similar to that of the comparative LCA used in the environmental analysis of shortlisted technologies in this study. In order not to compromise the environmental integrity of the EU ETS (avoiding the risk of internal carbon leakage) and avoiding a shifting of emissions towards Effort Sharing sectors, we propose that, in the short-term, only CCU processes which lead to permanent storage of the carbon should be incentivised, or processes where the production and use of the product occurs within a single installation.

A Piecemeal approach considers options in the Waste and circular economy policy framework and the Environmental pollution policy framework. Under the Waste Framework Directive, harmonised end-of-waste criteria and by-product criteria would allow for the categorisation of waste as either new products or by-products, allowing for greater integration of carbon-recycled products across the EU common market. The risk related to the possible presence of hazardous substances in reused materials should however still be mitigated by producers or ensured that it does not cause harm by specifying safe uses of the product. Under the Environmental pollution

[9] Guidelines for LCA (and techno-economic analysis) of CCU have been developed by a consortium of partners from TU Berlin, RWTH Aachen, University of Sheffield and IASS Potsdam, initiated and commissioned by The Global CO_2 Initiative and EIT Climate-KIC. See: https://www.iass-potsdam.de/en/research/development-standardised-guidelines-lifecycle-assessment-carbon-dioxide-conversion

[10] The aim of Innovation Deals is to either help lift any perceived barrier related to interpretation of the legislation, or use the flexibility in the existing legislation to help innovators achieve their goals and contribute to EU objectives.

policy framework, the IED is taken as a possible way to incentivise CCU processes which offer GHG and resource efficiency gains via the existing 'best available technique' and 'emerging technique' mechanisms. To recognise CCU processes as 'best available' or 'emerging' techniques, thorough assessments would need to be conducted. For now, the requirements for being categorised as emerging techniques seem more within reach due to the novelty of most CCU technologies and lack of information about their environmental impacts. This option should however not be seen as a priority as it would be unlikely to lift significant or undue barriers to CCU deployment.

A New CCU policy approach considers possible CCU-specific policy, although no new legislation is considered but a soft policy approach is proposed. The only option investigated is for the European Commission to collect knowledge about CCU and publish a Communication setting out the EU's position regarding CCU and common definitions. Policy objectives could also be set out across sectors and policy areas. The work would gather stakeholders to agree on what the EU should aim for with regards to CCU deployment and help unify the discourse around this complex set of technologies.

A No-new policy approach discusses the option of not offering new legislation for CCU. In particular we discuss in option 1 the possibility of not including CCU in the EU ETS in the near-term. While there are good arguments for doing so, such as the lack of information about the GHG benefits of specific CCU technologies, the CJEU's preliminary ruling on the Schaefer Kalk case must be implemented in some way. Furthermore, some form of recognition of CCU processes' potential GHG emission and resource efficiency benefits should be offered. Option 2 discusses not taking further policy steps, except with regards to financing, where balanced financing across different types of CCU processes could allow for the development of more resource-efficient and climate-beneficial technologies in different sectors.

4.8 Impacts of policy options

The ETS approach's short-term option risks incentivising CCU mineralisation processes, where permanent CO_2 storage is more likely than in other types of products from CCU processes, and at the expense of these other product clusters. Consequently, for applications which do not promise permanent storage, other non-ETS measures should be pursued. For instance, renewable fuels of non-biological origin have now been introduced into the RED II to count towards Member States' renewable energy targets and are incentivised via fuel blending quotas in the transport sector. Ensuring that the mechanism under the RED II works well means avoiding that these CCU fuels receive too much incentive such as double counting in different sectors.[11] The development of low-carbon alternatives where they are becoming available should not be hampered to the advantage of CCU fuels, such as hydrogen fuel-cell transport or electric mobility for road vehicles compared to aviation.[12] In the long-term, CCU fuels will have a potential to replace fossil fuels in sectors where alternatives may be limited, such as aviation fuels.

Some mineralisation routes offer the opportunity to solve two problems at the same time: waste ashes and slags from industry can be converted with CO_2 to useful products like building materials instead of being landfilled.

The long-term option of reforming the ETS points towards the development of project-based GHG accounting mechanisms for CCU. However, questions remain whether such a mechanism can ever be sufficiently robust in terms or monitoring, reporting and verification of emissions

[11] Christensen, A. and Petrenko, C. (2017). CO2-Based Synthetic Fuel: Assessment of Potential European Capacity and Environmental Performance.

[12] Transport & Environment. (2017). Electrofuels – what role in EU transport decarbonization?

and whether the administrative burden will be commensurate to the climate benefit of CCU technologies.

The new policy measures contained in the Piecemeal approach could potentially create a demand for CCU products, however more research is needed per product market cluster. Climate mitigation from carbon reuse can occur not only when CO_2 is captured and reused thereby replacing fossil feedstocks, but also as carbon-based materials (construction materials, polymers, etc.) are recycled, avoiding the need for extraction of new materials. By reducing the dependency on fossil fuels, the EU also would reduce its dependency on their import.

The New CCU policy option to publish a Communication on CCU presents important benefits for clarifying what CCU is and how it is approached in the EU. The document could have relevant societal impacts on creating a common understanding for policy-makers, industry and the public. This could in turn lead to better policy decision discussions.

There are good arguments to suggest that not including CCU in the ETS in the short-term is desirable and may not raise significant problems considering that CCU-based production capacity is likely to remain marginal in the next ten years. This is also the case when considering the relatively low climate mitigation potential of the technologies (in light of their difficult market penetration) and their very large need for renewable energy supply, competing with potentially more climate beneficial technologies.

1. Introduction

The utilisation of carbon dioxide in diverse production processes is referred to as 'Carbon Capture and Utilisation' (CCU) or 'Carbon Dioxide Utilisation' (CDU) (Jones et al., 2014) and together with material recycling of polymers is regarded as important element of 'Carbon Recycling' (CR) (Bringezu, 2014). This refers to technologies and processes which, either directly or following chemical transformation, use carbon dioxide as a component in materials or energy sources, thus rendering the carbon dioxide useful.

Despite commonalities in the possible capture of CO_2 from industrial emissions, CCU differs fundamentally from what is referred to as 'Carbon Capture and Storage' (CCS) technology. While these, as 'end-of-pipe' technologies, aspire to the permanent underground storage of CO_2, CCU offers the possibility of economically utilising CO_2 emissions as an alternative source of carbon, with the perspective of at least partly closing industrial carbon cycles.

As CO_2 is extremely inert, aids are usually necessary to enable it to play a role in chemical reactions, in order that materials of higher energetic value can be created. Such an aid could, for example, be the use of additional energy, either directly or in the form of reactants which are rich in energy, although these can also have a negative effect in the end, changing the total balance and reducing the potential for savings. Either alternatively or as a supplementary method, chemical catalysts can be deployed in order to develop processes which are energetically more efficient overall. The catalysis research which is necessary for this is a crucial factor for the development of CCU technology (Klankermayer & Leitner, 2015; Peters et al., 2011).

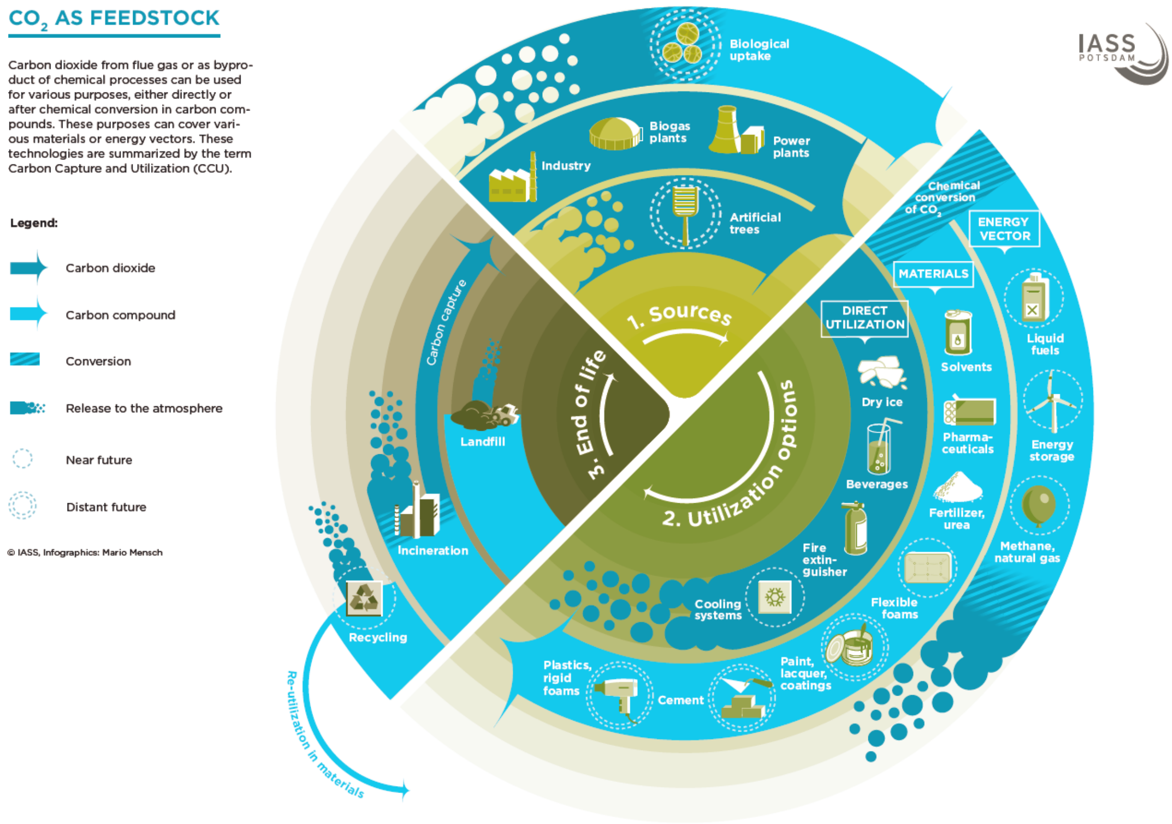
If CO_2 can be integrated into process chains as a substitute for energy rich compounds, the measure goes along with increased energy efficiency, such as in the case of Covestro (Materialscience, 2015). However, if CO_2 needs to be transformed into hydrocarbons, due to the additional energy required the choice of the energy source will be crucial for the environmental performance of CCU technologies. Then only adequate renewable energy sources will render CCU perform superior to that of conventional technologies to produce platform chemicals or polymers.

The CO_2 concentration at the source is the most important factor in deciding which technology to deploy for the capture of CO_2. Generally speaking, the higher the CO_2 concentration in the gas mixture from which the capture is to be carried out, the less energy per tonne of CO_2 captured and technical effort is required for the capture. CO_2 can potentially be extracted from numerous industrial sources, including industrial flue gases and large coal/gas-fired power plants with low concentration. The procedures which exist today already make it possible to provide large quantities of CO_2 of various degrees of purity. However, due to the costs of capture and the prevailing low demand for CO_2, such technology is not in widespread use, although it is available in principle.

1.1 CCU utilisation options

Figure 1 provides an overview of the various elements in diverse CCU processes. The image is sub-divided into sections in temporal order: CO_2 sources, possibilities for use, and end of life. In the 'possibilities for use' section the three central methods of use, i.e. direct utilisation (no conversion), utilisation as material, and utilisation as energy sources (after chemical transformation), are presented with respective examples of final products. All of the possible stations integrated in the figure are supplemented with a temporal dimension: no circle means 'on the market'; one circle means 'technically feasible, but not yet commercially possible to implement'; two circles means 'in development'.

The blue arrows represent the CO_2: dark is CO_2 itself; light is transformed carbon dioxide compounds; and dotted an emission. The circular image illustrates, in addition, at which locations on the way to a CO_2 cycle gaps exist that still need to be closed. These include, in particular, the 'end of life' phase with the options of incineration, landfill or recycling and (renewed) emission after direct utilisation or utilisation as energy sources.



Source: IASS Potsdam http://www.iass-potsdam.de/en/research/emerging-technologies/ccu

Figure 1: Overview of CO_2 sources, utilisation options and end of life considerations

1.2 Assessment of environmental and climate protection potential

To date there are still no reliable estimates for the total actual implementable saving of CO_2 emissions via CCU technologies, due to the fact that the usable emissions described do not correspond with the actual saved emissions: the emissions savings can vary greatly, depending on the employed technology, i.e. can be smaller or larger than the used amount of CO_2 emissions, depending, in particular, on the energy to be spent during the process and the emissions associated with that. It is even possible that an increase in emissions will occur. Therefore, a full individual life-cycle assessment (LCA) is necessary to identify the environmental effects of each technology application.

The availability and price of renewable power are the critical factors which currently render most CCU technologies not yet commercial, although these are changing rapidly in a positive direction, potentially passing several financial tipping points for various CCU processes. At the same time, CCU technologies on a life-cycle-wide basis require material resources for installations such as wind power generators. For some CCU production chains the savings of CO_2 compared to the reference case are higher than the additional material resource requirements, while others would not seem recommendable considering the trade-off (Hoppe et al., 2017).

During any comprehensive assessment it is also necessary to take into consideration the duration of storage of CO_2 in the materials. In the case of CCU applications the utilised CO_2 is only bound in the products for the duration of their life-time. The expected variation of the duration of storage can be days or weeks (fuels), or years (plastics), or even centuries (for building materials similar to cement or insulating materials) (Styring et al., 2011; von der Assen et al., 2013).

If CO_2-based products are assumed to be substitutes for fossil-based products and thus provide the same service and would be used and disposed of according to the same patterns as conventional products, the focus of the life-cycle-wide analysis may lie in the cradle-to-gate phase. If CCU products can be produced with less environmental impact (including GHG emissions) than fossil-based ones, an environmental benefit can be asserted, independent of the storage time of CO_2 in the products.

However, CO_2 products can be entirely new products replacing carbon-intensive products, such as carbon fibres replacing steel, aluminium or concrete. Such products are still at early development stages, so they have been excluded from the scope of this study.

It is necessary to consider all applications in their own right and to individually calculate the potential of each industrial method for savings. For an overall evaluation optimisation of processes due to the introduction of CCU technology also plays a role that can lead to indirect emission savings. Since the majority of the relevant technologies are still at early developmental stages, such assumptions are, at the present moment, difficult to predict.

The degree of the technical development varies greatly between applications of CCU. While first applications of some of these novel technologies have already reached the market, such as, for example, E-Gas by Audi or polyols by Covestro, others are still at a very early development phase. Consequently, technical hurdles to be overcome vary greatly, are specific to each technology and, if possible, need to be assessed individually. While many applications are seemingly close to technical feasibility, the next steps to their implementation will depend on their promise of economic advantage, and on the favourable development of external conditions, such as, for example, funding or tax incentives or CO_2 pricing.

1.3 CCU regulatory challenges and developments, and EU financing options

The EU led the world by developing a regulatory framework for CCS through Directive 2009/31/EC on the geological storage of carbon dioxide and establishing an Emissions Trading Scheme as provided for in Directive 2003/87/EC *Establishing a scheme for greenhouse gas emission allowance trading within the community*. The EU's ratification of the Paris Agreement, together with the ongoing reforms to the EU Emissions Trading System (EU ETS) and activities under the Strategic Energy technology (SET) Plan process, continue to demonstrate the EU's commitment and willingness to address climate change and provide support to technologies such as CCS and CCU(S). The EU's legal framework encompasses a number of legislative texts which can affect novel promising CCU technologies.

Although there has been a significant development of regulatory framework in both the EU and many other jurisdictions over the last decade, there seems to be a lack of incentives and still some perceived hurdles for full-scale deployment. Although these hurdles do not stop stakeholders from utilising CO_2 in their industrial processes, as has been seen in the industries and production methods identified above, these represent relatively modest quantities of CO_2 and the activities are not initiated for the purpose of – nor result in – any climate change mitigation.

The question is to what extent the regulatory framework as it is being developed can positively or negatively impact the development of promising CCU technologies, whether it should be adapted to accommodate and incentivise CCU activities as climate change mitigating measures, and if that should be done by amending the current regulatory framework for CCS or by introducing new instruments.

1.4 Purpose and methodology of this study

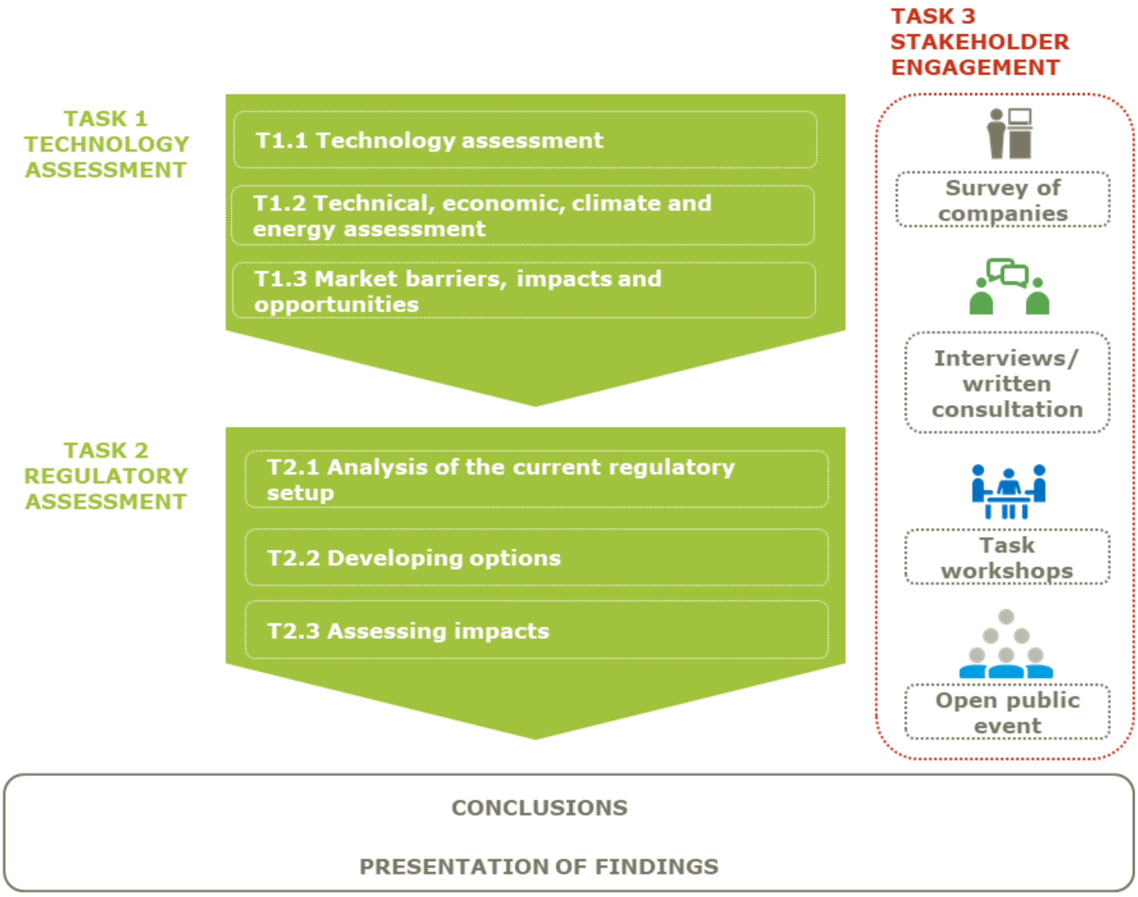
This study has three objectives:

- to assess the readiness and map the roll-out of different CCU technologies in order to clarify which types of technologies are viable for support, including from the planned Innovation Fund under the EU ETS;
- to examine the EU regulatory set up related to the technologies concerned and assess whether specific provisions are necessary to reflect the contribution of these innovative technologies to climate mitigation while preserving the environmental integrity of the relevant legislation; and
- to engage with stakeholders for better understanding of the technologies and the legislative setup.

See also the terms of reference for this study in Appendix 6.

To meet the three goals a methodology was composed which consists of three tasks. An overview is presented in the figure below.

Figure 2: Overview of study methodology



Technology assessment (Task 1) was the first task of this project. It was mainly based on desk research; however, due to the limited availability of certain data, stakeholder consultations were also conducted to fill in data gaps and deepen the findings.

Regulatory assessment (Task 2) followed up on Task 1 in that it departed from the short-list of technologies as case studies for regulatory assessment. It relied on desk research and stakeholder consultations to produce informed results based on a wide range of expert input.

Stakeholder engagement (Task 3) was an ongoing activity for the duration of the project designed to contribute to the study by way of the collection of data from stakeholders, complementing potential gaps in the desk research, ensuring that the study provides up-to-date information in the field of CCU, and also providing the opportunity to the stakeholders to be involved in and contribute to the development of EU policy on CCU.

2. Task 1: Technology Assessment

2.1 Purpose and approach

In order to allocate European funding economically, efficiently and in an ecologically worthwhile way, it is necessary to **identify and assess technology applications** that are sufficiently mature regarding their technological development so that they can be expected to be ready for demonstration at pre-commercial scale within the next decade (up to 2030) and could possibly **provide an environmental advantage**.

The overall approach to the technology assessment in Task 1 combined a comprehensive data-oriented step (literature review and desk research) with direct consultations of relevant companies and research organisations (optionally as an oral interview or as a written submission).

The objective of this task was to gather up-to-date information on CCU technologies that can reach a pre-commercial demonstration level in the period 2021–2030. Following the definition of **technology readiness levels** of the European Commission, as published in the General Annex of the Horizon 2020 work programmes (EC, 2015), TRL 7 characterises a system prototype demonstrated in a relevant environment. To reach TRL 7 within the given timeframe up to 2030, only technologies that have progressed today beyond TRL 3 (experimental proof of concept) and processes which are not too complex to upscale can be considered relevant. Therefore the main focus of the assessment is on technology applications with TRL 4 or higher, where basic technology components are validated in the relevant environment.

An assessment of the development of a new technology via TRL is sufficient to describe the current state and to make assumptions about future development. Nevertheless, a necessity for positive future development is not inherent in TRL classification, as the development might get stuck or end completely. This so-called 'valley of death' refers to a gap of funding between basic technology development (push technology development, up to TRL 4/5) and application specific technology development (pull technology development, after TRL 6/7) (van der Veen et al., 2013). Funding as proposed in a European Innovation Fund, and also Horizon 2020 and the future Horizon Europe programme, might help to overcome this valley of death.

The assessment and selection process in this report comprised four steps, depicted in Figure 3, aiming first at selecting the most promising CCU technologies (Task 1.1: Identification and selection of technologies). In the first step a longlist of CCU technologies and routes was compiled and their respective TRL was determined according to the available data (step 1), resulting in a preliminary TRL-based shortlist (step 2). A multi-criteria assessment was used to evaluate the shortlisted CCU applications (step 3), leading to another selection step for the environmental assessment that followed in Task 1.2 (step 4). **All steps of the workflow are explained in detail in the respective Section.**

As a result of the technology assessment in Task 1 of this study a **shortlist** of such technologies was drawn up, including a **multi-criteria assessment** of shortlisted technologies and a **life-cycle assessment** of selected technologies that can reuse carbon dioxide industrially in the future.

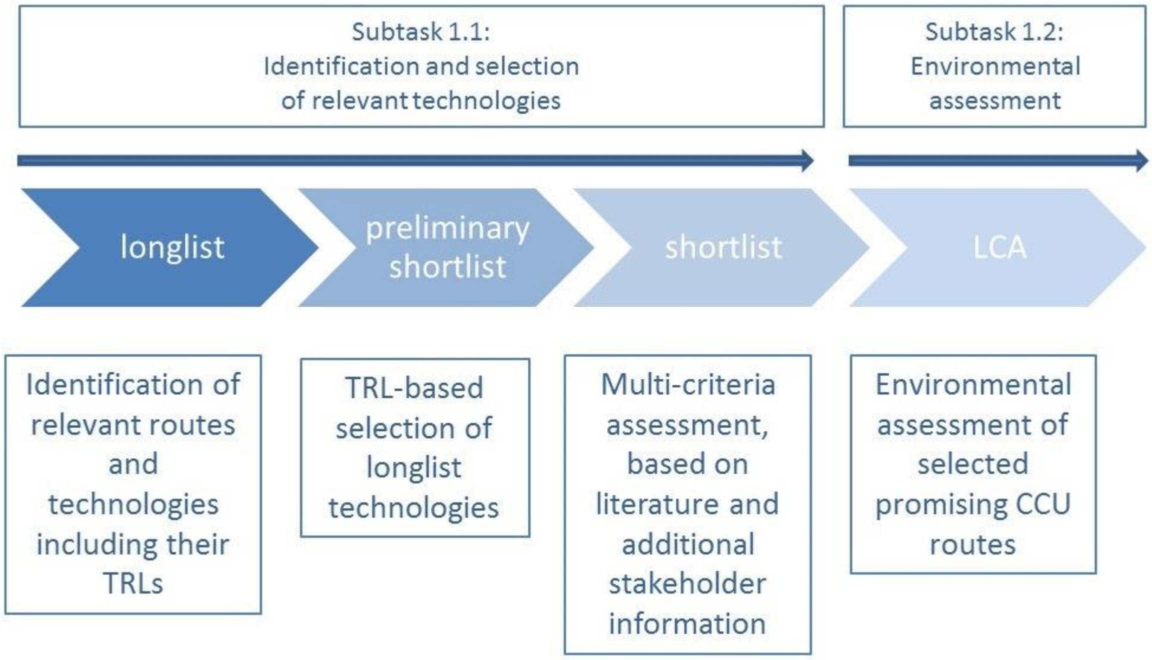


Figure 3: Workflow technology assessment Task 1

2.2 Task 1.1: Identification and selection of promising CCU technologies

The objective of Task 1.1 was to identify and select promising CCU technologies, starting out with a compilation of a technology longlist that would be assessed with regard to their TRL and also several aspects and then narrowed down to a shortlist for further assessment.

2.2.1 Longlist: identification and TRL-based selection

A comprehensive longlist of CCU products was compiled by way of an extensive literature review seeking information about the products' underlying conversion route and technology, their maturity, and economic and commercial, as well as environmental, indicators. This review did not include only up-to-date scientific literature, but also CCU databases and information available from the industry and current research programs.

The output of the data collection process described above was the technology longlist shown in Section 4.1 of the Appendix, which constitutes a database for possible CO_2 conversion products and respective routes, technologies and projects.

Methods: Assessment categories longlist

The technology longlist comprises the following categories:[13]

Product

The CCU product that is produced with the respective technology. A CCU product can be a single product, such as methanol, or a group of products, such as hydrocarbons or carbonates. For every technology pathway the produced product is listed separately, thus one CCU product can appear several times if it can be obtained by various conversion routes and technologies.

[13] For an overview, see end of this Section.

CCU route

As mentioned in Section 1 (Introduction), different classification approaches exist for the broad range of CCU technologies. The main classification criteria for the longlist were the transformation routes, rather than any functional or technical grouping. The general routes have been chosen based on Mikkelsen et al. (2009). That article is a fundamental and a much-cited review for possible carbon dioxide transformations. The article distinguishes between six different CO_2 transformation categories, which are listed as follows.

- Chemical – non-hydrogenative
  Chemical conversion of CO_2 without hydrogen as a co-reactant. The CO_2 molecule is incorporated into the product (e.g. polymers).
- Chemical – hydrogenative
  Chemical conversion of CO_2 with hydrogen as a co-reactant and reduction of the carbon atom (e.g. methanol).
- Biological
  CO_2 conversion by photosynthesis (plants, e.g. algae with high reaction efficiency) and reduction of the carbon atom.
- Electrochemical
  Reduction of the CO_2 carbon atom by adding electrons; the electron source can either be an applied current or a semiconductor exposed to light (photocatalysis).
- Photochemical
  Reduction of the CO_2 carbon atom by solar energy (artificial photosynthesis).
- Inorganic
  Fixation of CO_2 in inorganic compounds (carbonates, e.g. Ca- and Mg-carbonates or soda ash).

The CO_2 conversion step is decisive for a product's classification with regard to the CCU route. For some products the production process consists of several transformation processes of different chemical routes; for example, mono oxymethyl ether (OME) by Ineos in Germany is produced via CO_2-containing methanol, thus classified as 'chemical-hydrogenative', because the methanol is produced by combining H_2 with CO_2.

Reaction specificity

The selectivity of a reaction is a selection criterion to show whether a technology produces one single product or multiple products (a product group); for example, the Fischer-Tropsch synthesis produces a mixture of different hydrocarbons, such as synthetic diesel, gasoline, kerosene and others rather than one specific product. The output of the Fischer-Tropsch synthesis always comprises several products from one technology. This principle is indicated with the specificity criteria: 'Low specificity' indicates that the product comprises a group of products; 'High specificity' indicates that a single product is produced. From process descriptions it is not always determinable if a single product or a group of products is produced. The DreamReactions and DreamPolymers projects in Germany usually evaluate product groups, but parts of the process chains may be used to produce one specific product, such as Covestro's polyurethanes from CO_2 containing polyols. Polyols and polyurethanes are product groups, but the respective project examines a specific reaction to produce flexible polyurethane foam, one possible application of polyols.

Chemical group

CCU products can be allocated to different chemical product groups, such as alcohols or carboxylic acids. Different classification schemes exist in literature. The longlisted products follow the categorisation in Figure 4, as defined in Styring et al. (2011), when possible.

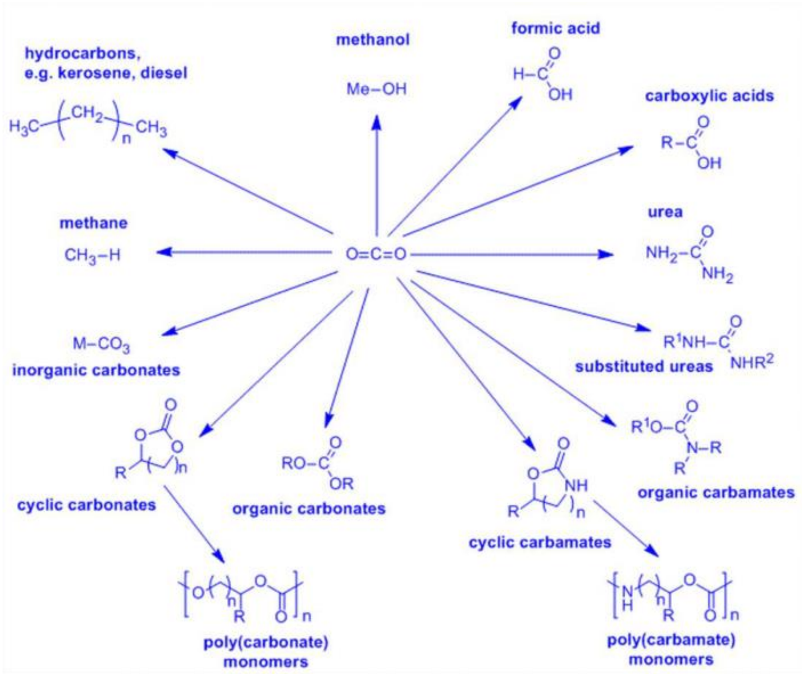


Figure 4: Overview of chemical groups from carbon dioxide (Styring et al., 2011)

CO_2 use

Whether CO_2 is incorporated into a product directly or indirectly by a precursor CCU product is indicated by the 'CO_2 use' categorisation:

- Direct
  CO_2 is incorporated in the product directly as an educt in the reaction, e.g. direct hydrogenation of methanol from CO_2 and hydrogen. A direct process always has CO_2 as a carbon source on the educt side in the reaction.
- Indirect
  CO_2 is not incorporated in the respective technology, but used indirectly from precursor CCU products, e.g. production of polymers (polyoxymethylene) from formaldehyde from methanol from methane. Formaldehyde, methanol and methane could theoretically all be produced directly from CO_2. Additionally, formaldehyde can be produced from methanol and methanol can be produced from methane. If one of these educts is produced via CCU, the production of polyoxymethylene becomes a CCU process. The complete production process of polyoxymethylene polymers from CCU educts will have different economic and environmental impacts depending on which input is the CCU educt (methane, methanol or formaldehyde). The polymerisation of polyoxymethylene itself does not consume any CO_2.
- Direct & indirect
  Conversion processes may utilise CO_2 directly as an educt and indirectly through another educt that can be derived from a CCU process itself. The economic and environmental performance will vary significantly, depending on whether the educts are produced from CCU. An example is the production of acetic acid from CO_2 and methane: CO_2 is consumed directly in the reaction and methane can be supplied conventionally (fossil-based) or via CCU methane production, which would constitute an additional indirect CO_2 usage in the process.

Indirect uses require a deeper knowledge of the process and the respective process chain. Direct & indirect has a larger number of variables and requires more knowledge of the process chains, especially if many educts potentially originate from CCU processes. The processes are determined as CCU, but indirect CO_2 usage has to be evaluated specifically for each process and case.

Carbon input
Carbon input indicates the CO_2 source for the process chain. The grouping is similar the 'CO_2 use' category described above, but gives additional information on how CO_2 as a carbon source is incorporated into the reaction:

- <u>CO_2 only</u>
  CO_2 is used as the only carbon source in the process.
- <u>CO_2 + CCU organic educts</u>
  CO_2 and potential organic CCU products (conventional chemicals that can be replaced by an organic CCU product).
- <u>CCU educts</u>
  The process uses potential CCU products, but no CO_2 directly.
- <u>CO_2 + other non-CCU organic educts</u>
  The process uses CO_2 directly, but also additional organic carbon sources that cannot be replaced with CCU given the state of science.
- <u>CO_2 + inorganic educts</u>
  The process uses CO_2 directly and other inorganic educts.
- <u>CO_2 + potential CCU educts</u> (process/project specific)
  The process uses CO_2 directly and other educts that can technically be produced via CCU technology (e.g. ethylene oxide, which is conventionally not produced via CCU but theoretically could be produced with CO_2 as the carbon source). The described process uses in addition to CO_2 conventional educts that could be replaced with CCU products.
- <u>CCU educts + other educts</u>
  The process uses potential CCU products and other chemicals as educts that cannot be replaced with CCU products.

The carbon source category helps to evaluate representative process groups. 'Direct use' only would not differentiate technologies such as mineralisation from direct hydration or industrial reactions that use CO_2 from fossil sources, such as salicylic acid. Thus 'carbon input' is complementary to 'CO_2 use' and allows a detailed clustering based on the 'CO_2 use' category.

Technology identification
Technology identification is an identifier for the process technology that includes the name and principles of the process as well as additional information or specificity. A product may be derived via multiple reactions and multiple respective technologies, but the technology in combination with reaction is the core information about the process. The combination is necessary, as the specific name of the technology and reaction are not unique. Some processes have specific names, such as 'Steelanol', but other processes use more generic technological terms. The project and source categories may give additional information about where the information for the technology and reaction categories has been taken from.

Reaction
The reaction is an essential attribute of any chemical process. The reaction shows the educts and products of a technology in a comparable manner and helps to identify differences between similar technology descriptions (see technology identification above). If stoichiometric data for a CCU reaction is available, the calculation of the theoretical stoichiometric carbon binding potential in the product is possible.

Usage
A differentiation into product usage groups is beneficial, as the lifespan or retention time depends on the final use and application of the given CCU product. Energy carriers and fuels

only keep the captured carbon bound for a short time, since the CO_2 is immediately released when the fuel is used. Material products, such as construction and building materials, bind the carbon atoms for a longer time (up to a century) and consequentially have a higher mitigation potential.

Ademe (2014) distinguishes between three different fundamental groups referring to the final use of a CCU product. Following this definition products are classified into three usage groups:

- Chemical
  Ademe (2014) calls one category 'chemical products'. Chemicals are usually intermediate products used in the chemical industry. Depending on their volume and value they can be split further into bulk-chemicals or fine-chemicals (Otto, 2015).
- Fuel
  Ademe (2014) describes this category as 'energy products'. Their main purpose is to store energy until the energy is released. This applies to fuels (e.g. diesel, kerosene, etc) or energy storage media (e.g. methanol) to store excess energy from renewable energy sources.
- Material
  Ademe (2014) refers to certain materials as 'inert materials'. Materials cover the material usage of products which are inert or not inert. Materials are usually inert, but we did not choose to use the word 'inert', as it may play a more important role in terms of CO_2 storage in the future ETS, where being 'inert' will be a specific prerequisite for storing carbon for longer periods of time. Materials in detail can be plastics, building material substitutes or other materials that will be derived from CCU processes. Their lifespan depends on the end use of the given CCU product. Examples would be applications in the automotive sector (e.g. polyurethane car seat cushions) or in the construction sector (e.g. concrete building blocks). Materials in general are suited for integration to the circular economy, as the overall lifespan can be elongated via material recycling.

The grouping developed by Ademe (2014) is general, but allows a more detailed clustering in a second step if required. The concept gives enough information for an initial clustering of the CCU processes.

Projects
Completed, ongoing or planned projects have been compiled in this category. For the evaluation and the determination of most products' maturity information on concrete projects is crucial.

TRL
To determine the maturity of the CCU processes the Horizon2020 categories have been used to identify the 'Technical Readiness Levels' (TRL). The definitions are listed in Table 1.

Table 1: TRL Definitions (Horizon 2020)

TRL	Horizon 2020 Description from the European Commission (2015)
1	basic principles observed
2	technology concept formulated
3	experimental proof of concept
4	technology validated in lab
5	technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
6	technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
7	system prototype demonstration in operational environment
8	system complete and qualified
9	actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

The classification of the CCU products into one of the nine TRL categories was based on information found in project descriptions or assessment reports. Some processes had differing classifications in literature, and for other products there was no information available regarding the maturity of their technology. In these cases the classification was first estimated according to our best knowledge. A request for further information on the specific TRLs was then incorporated in the stakeholder interviews mentioned above. In some cases additional information was generated this way and marked accordingly in the longlist/shortlist.

Readiness levels were based on the process technology. Indirect processes based on precursor CCU products were assigned the level of the precursor CCU process.

The technical maturity of longlisted products, indicated by their TRLs, was the only assessment criterion and decided whether a given product was subject to further consideration in the shortlist. Products and their respective technologies and demonstration project with TRLs between 5 and 8 were transferred to the shortlist, i.e. a product’s technology must be at least validated in its relevant environment but not be proven in its operational environment, i.e. commercially viable (Horizon 2020). If there was no information on the TRL of, or specific projects involving, a given product, it was not considered further due to lack of data.

Table 2: Overview of assessment criteria, longlist

Criterion	Description
Product	A CCU product that is produced with the respective technology. A CCU product can be a single product or a group of products.
CCU route	The main classification criteria for the longlist were six transformation routes, chosen based on Mikkelsen et al. (2009). For some processes the production process consists of different chemical routes.
Reaction specificity	The selectivity of a reaction was a selection criterion to show if a technology produces one single product or multiple products (product group).
Chemical group	The CCU products can be classified into different chemical product groups, such as alcohols or carboxylic acids. The longlisted products follow the categorisation in Figure 4, as defined in Styring et al. (2011), when possible.
CO_2 use	Whether CO_2 is incorporated into the product directly or indirectly by a precursor CCU product is indicated by the 'CO_2 use' categorisation.
Carbon input	Carbon input indicates the CO_2 source for the process chain. The grouping is similar the 'CO_2 use', but gives additional information on how CO_2 as a carbon source is incorporated into the reaction. The category carbon source helps to evaluate representative process groups.
Technology identification	This category is an identifier for the process technology, which includes the name and principles of the process as well as additional information or specificity.
Reaction	The reaction is an essential attribute of any chemical process. The reaction shows the educts and products of a technology in a comparable manner and helps to identify differences in similar technology descriptions. If stoichiometric data for the CCU reaction is available, the calculation of the theoretical stoichiometric carbon binding potential in the product is possible.
Usage	A differentiation in product usage groups is beneficial, as the lifespan or retention time depends on the final use and application of the CCU product.
Projects	Completed, ongoing or planned projects have been compiled in this category. Information on concrete projects is crucial for the evaluation and the determination of the maturity of most products.
TRL	To determine the maturity of the CCU processes, the Horizon2020 categories have been used to identify the 'Technical Readiness Levels' (TRL).

Excluded processes and products

The longlist does not include the following products and processes that have been deliberately excluded for different reasons, as stated below:

- Direct (physical) use of CO_2 that is not subject to chemical conversion of CO_2 (e.g. food preservation, beverages).
- Established chemical routes that utilise CO_2 (e.g. urea production) and are thus not novel.
- No value-adding products where CO_2 is converted, e.g. waste treatment (e.g. bauxite treatment).
- Fine and high-value chemicals have not been considered in the longlist due to their small production volumes and associated CO_2 uptake potential (no significant contribution to climate mitigation); see Otto et al. for further CCU routes.
- Biofuels have been excluded since the carbon source is usually from crops (1st generation biofuels) or biomass (2nd generation biofuels). Biofuels are beyond the scope of this study; material products from microalgae have been included in the longlist since a net CO_2 consumption in the process in possible.
- Enhanced hydrocarbon recovery (EHR) applications that might technically be considered a CO_2 utilisation application have been excluded, since their primary purpose is the extraction of fossil resources

Results: technology longlist

For usability reasons the detailed longlist has been included in part 1 of Appendix Task 1. For details, please refer to the Appendix. Here only essential information will be provided.

The longlist consists of 130 different CCU products from different routes and functionalities (see Figure 5). The most represented routes are 'chemical non-hydrogenative', with 56 products or product groups, and 'chemical hydrogenative', with 43 products or product groups. Over 60% of all products use CO_2 directly as a carbon source and 26% of all products use CO_2 as the only carbon source in the reaction.

Many product routes (64 of the 130) have a low TRL, between 1 and 3, i.e. their technologies have not yet been validated in laboratory environment but experimental proof has been confirmed. On the other hand, there are many products with TRL 7 and above, i.e. the given system has been demonstrated or even proven in its operational environment. Intermediate TRLs are not so prevalent. CCU products seem to be either at a very early development stage or already at least in the demonstration phase.

The TRL distributions of the individual CCU routes mainly show the same pattern. Products obtained through the 'chemical hydrogenative' and 'chemical non-hydrogenative' routes have either a relatively low (1–3) or a high (7–9) TRL. Products from biological, electrochemical or photochemical conversion are generally at a low maturity level (TRL 1–3). TRLs of products derived from inorganic synthesis are distributed equally over all maturity levels.

After reviewing the technological maturity of every product or product group of the long list, 15 representative products via different technologies were in relevant TRLs (5–8) and transferred to the shortlist for further in-depth assessment.

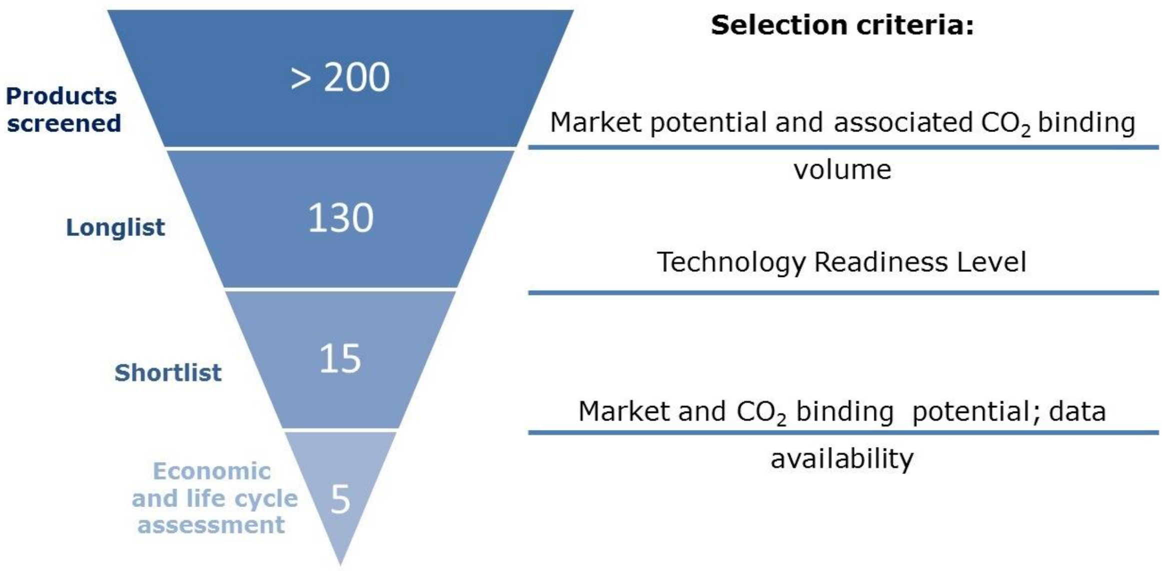


Figure 5: Selection process and results – technology longlist

The shortlisted CCU products cover various technology routes; however, the most common route is 'chemical hydrogenative', due to the large production and import volume in the EU and advanced maturity level. The shortlisted products are listed in **Table 3**.

Table 3: Shortlisted products.

Product	Abbreviation
Biological	
Ethanol	EtOH
Methane	Methane
Proteins from microalgae	Proteins
Chemical hydrogenative	
Ethylene	Ethylene
Methane	Methane
Methanol	Methanol
Oxymethylene ether (OME1)	OME1
Polyethylene (PE)	PE
Polyoxymethylene (POM)[14]	POM
Polypropylene (PP)	PP
Propylene	Propylene
Synthetic fuels	Fuels
Chemical non-hydrogenative	
Polycarbonate (BisA-PC)	BisA-PC
Polyols for Polyurethane (PU) foams production	PU
Inorganic	
Calcium carbonate	CC
Sodium carbonate	SC

2.2.2 Shortlist: data-based multiple-criteria assessment

Methods: Assessment criteria shortlist

The technology assessment of the shortlisted products was conducted via a rating matrix[15] including the following criteria on which data was collected either from literature (e.g. Bazzanella & Ausfelder, 2017) and desk research or through individual collection of information via written consultation or in interviews, as described below.

The criteria for shortlisted CCU technologies can be classified into three assessment categories (for an overview, see the end of this Section).

[14] Polyoxymethylene also referred to as polyacetal (PA).

15 Please refer to 'Technology Shortlist' in the Appendix.

Technology maturity

Criteria in this category indicate how mature the technology to produce the given product is and what advancements are needed to accelerate the commercialisation thereof and in what time scale.

TRL – see above (longlist).

Time to commercialisation
The expected time to commercialisation also indicates how close to being on the market the given product is and gives information about the next steps. This information is mainly project-specific and was primarily derived from written stakeholder consultations.

Economic and commercial assessment parameters

Assessment parameters in this category elucidate the competitiveness in terms of price and other financial indicators of CCU products and the production & import volume in the EU. Production & import volumes are of particular interest together with CO_2 savings to estimate the overall CO_2 reduction potential of the given product.

Financial indicators[16]
Financial indicators such as capital costs (CAPEX) or operational costs (OPEX), as well as profitability figures such as Net Present Value (NPV), were collected from literature or web searches. Financial indicators enable a statement to be made with regard to the given product's competitiveness and economic viability for the decision maker. The indicators can vary widely between different projects, since they are dependent upon many variables, e.g. production scale or location.

Product price
Price is fundamental for assessing a product's competitiveness. A CCU product must be competitive with either the conventional product's market price or with the price on the sustainable market, depending on the target market (e.g. the price of fuels derived from CCU can be compared to a fossil fuel's market price or to the price of biofuels). Price data for conventional products was mainly derived from the ProdCom database. If there was no entry in that database, an Internet search was carried out to fill the gap.

Total EU production & import volume
A product's total EU production & import volume is made up by the total European production volume plus imports into Europe. This number cannot display the initial market volume or future market developments, but rather give an idea of the magnitude of the material volume that can be replaced in Europe. Production volume and imports are mainly derived from the ProdCom database and show the total volume produced by all manufactures in one year. If there was no entry in that database, an Internet search was carried out to fill the gap.

Environmental assessment parameters

This category includes the theoretical CO_2-binding potential derived solely from the chemical reaction and the functional utilisation and associated CO_2 utilisation duration (retention time) within the given product. At this stage data availability for a full LCA was examined.

16 Financial indicators should include cost of production. The data collection among stakeholders is still in process. The paragraph will be changed accordingly in the final report.

LCA data availability
This column indicates if there was enough data available to conduct an LCA and thus is essential for the further consideration of the given product. If there was no detailed data on technological principle(s) and material and energy inputs, an LCA was not possible. Openly accessible full LCA for promising products have been discussed and evaluated in a separate chapter.

CO_2-binding capacity
CO_2-binding capacity, stated in kg of CO_2 per kg of generated product, was derived from the chemical reaction (if available). This indicates the stoichiometric amount of CO_2 that is theoretically bound in all products without examining the actual material and energy requirement for the production process or potential yield losses. For synthetic fuels the carbon-binding capacity has been estimated, due to the lack of product molecular formula. The molecular formula for conventional diesel (CAS 68334-30-5) stated by ECHA ,C92H182, is assumed for calculations using the reaction provided by Sunfire (UBA, 2016).

Product usage – see above (longlist).

Retention time
The retention time, given in years, quantifies the duration the CO_2 is stored in the respective product and depends on the usage of the product. The assumed time spans are estimates to distinguish the final usages. The assumed retention time is one year if the CO_2 is released after a short use-phase up to one year. This is the case with, for example, fuels, where CO_2 is emitted in the flue gas if the fuel is burned. A retention time of 10 years is assigned for materials (e.g. polymers) where the CO_2 is stored for a longer period until the product's use-phase ends. Polymers can be materially recycled or burned as a waste material to produce energy. For materials recycling periods are possible. Carbonation products, such as minerals, are materials with a long retention time; the retention time thereof has been assumed to be 50 years, but may vary depending on the life-time of the building. Products from carbonation are mainly building materials or aggregates that are used in construction and thus have a longer CO_2 use duration than, for example, polymers. All assumed retention times are estimates based on average material uses, in reality the time is highly depending on the specific use-phase, even if identical use categories are assumed. The determination of the retention time is necessary to show the different utilisation categories of the products in the shortlist.

Initial desk research to collect the required information for each product and each criterion on the shortlist was conducted. Supplementary information from stakeholder consultations was added to the matrix (See shortlist in Appendix Section 4.3, blue font colour, marked with *).

Table 4: Overview of assessment parameters, shortlist

Category	Criterion	Description
Technology maturity	TRL	See longlist criteria.
	Time to commercialisation	The expected time to commercialisation additionally indicates how close to being on the market the given product is and gives information about the next steps.
	Financial gap for large-scale demonstration	This criterion describes how large the necessary investments in order to achieve the respective technological maturity are and how much funding

	projects	is potentially available.
	Technical advancements necessary	This criterion indicates the major technical hurdles that need to be overcome and identifies break-off criteria.
	Replication potential	Is the technology site- or location-specific? What is necessary to replicate the technology? Where could the technology be applied or replicated?
Economic and commercial criteria	Financial indicators	Financial indicators, such as capital costs (CAPEX) and operational costs (OPEX), as well as profitability figures such as Net Present Value (NPV).
	Product price	A CCU product must be competitive with either the conventional product's market price or with the price on the sustainable market, depending on the target market.
	Total EU production & import volume	This number cannot display the initial market volume but rather give an idea of the magnitude of the production & import volume in Europe. Production volume and imports are mainly derived from the ProdCom database and show the total volume produced by all manufactures in one year.
Environmental criteria	**LCA data availability**	This column indicates if there was enough data available to conduct an LCA and thus is essential for the further consideration of the given product. > See the Section on LCA.
	CO_2-binding capacity	CO_2-binding capacity stated in kg of CO_2 per kg of generated product was derived from the chemical reaction (if available). This indicates the stoichiometric amount of CO_2 that is theoretically bound in all products.
	Product usage	See longlist.
	Retention time	The retention time, given in years, quantifies the duration the CO_2 is used in the respective product and depends on the usage of the product. The assumed time spans are estimates to distinguish the final usages.

<u>Results: Technology shortlist</u>[17]

17 For all details of the assessment and a full reference to all sources, please refer to the shortlist in part 2 of Annex 1. For usability reasons, here the results will solely be summarised and discussed.

The screening shows the products derived from CCU technologies that have the largest estimated potential in terms of EU economic value (shown in column 5 of Figure 6) and overall CO_2-binding potential, along with their respective retention times (shown in Figure 7 and Table 5). Financial parameters are estimates based on total European production & import volume and thus represent the 'best case', i.e. that every manufacturer would produce the given product via the respective CCU technology. The CO_2-binding potential per product mass also assumes the 'best case', meaning if the reaction is stoichiometric.

Product	Total EU Production and Imports [Mt/year]	Share of Imports	Product Price [EUR/t]	EU Economic Value [billion €]
Proteins from microalgae	20.00	95.00%	13000.00	260.00
Synthetic fuels	167.19	0.00%	1527.44	255.37
Methane	367.48	76.20%	200.00	73.50
Mono oxymethyl ether (OME1)	50.16	0.00%	1264.50	63.42
Calcium carbonate	261.45	0.55%	107.00	27.98
Ethylene	17.70	1.69%	697.00	12.34
Polypropylene (PP)	11.23	8.06%	974.00	10.93
Propylene	13.20	2.50%	595.00	7.85
Polyols for polyurethane (PU)	3.29	1.52%	1746.00	5.74
Polyethylene (PE)	2.88	29.75%	1051.00	3.03
Ethanol	5.16	1.94%	582.28	3.00
Polycarbonate (BisA-PC)	1.26	7.94%	2250.00	2.84
Methanol	8.04	85.07%	160.00	1.29
Sodium carbonate	9.57	22.68%	90.09	0.86
Polyoxymethylene (PA, POM)	0.21	0.00%	2780.00	0.58

Figure 6: Depicted results of the economic evaluation based on the shortlist evaluation (in Excel)

Total EU production & import volume (column 2) was calculated by adding the European total production volume to the volume of imports into the EU.[18] **Share of imports** (column 3) indicates how much of the total volume is currently made up by imports into the EU. This is an indicator of how the replacement of the conventional product could potentially impact domestic production sites in the EU. The **product price** (column 4) is the current market price of the given conventional product from the ProdCom Database traded in the EU. If price data from ProdCom was not available, other sources have been considered (see references for the shortlist, Appendix 4.2). **EU economic value** (column 5) was calculated by multiplying the total volume of the given conventional product by the respective product prices. This figure indicates the dimension of the total value generation of the products, because the higher the price the more advanced the product generally is in terms of its process and value chain. Proteins and synthetic fuels have the largest theoretical EU economic volume. The price for proteins from microalgae that can be used to make animal feed is highest. The import dependency is highest for methanol, with 85%.

18 For some products there was no information on import volume. The total production & import volume is thus underestimated compared to other products.

Product	CO_2 Binding Capacity [kg CO_2/kg product]	CO_2 Binding Volume [Mt CO_2/year]	Estimated Retention Time [years]	EU Economic Value [billion €]
Proteins from microalgae	1.80	36.00	1	260.00
Synthetic fuels	3.14	524.98	1	255.37
Methane	2.74	1008.29	1	73.50
Mono oxymethyl ether (OME1)	1.55	77.88	1	63.42
Calcium carbonate	0.44	114.96	50	27.98
Ethylene	3.14	55.54	1	12.34
Polypropylene (PP)	3.14	35.22	10	10.93
Propylene	3.14	41.42	1	7.85
Polyols for polyurethane (PU)	0.43	1.41	10	5.74
Polyethylene (PE)	3.14	9.05	10	3.03
Ethanol	1.91	9.85	1	3.00
Polycarbonate (BisA-PC)	0.17	0.22	10	2.84
Methanol	1.37	11.04	1	1.29
Sodium carbonate	0.21	1.99	10	0.86
Polyoxymethylene (PA, POM)	1.47	0.31	10	0.58

Figure 7: Depicted results of the CO_2-binding capacity evaluation based on the shortlist evaluation (in Excel)

Results concerning the environmental screening criteria of shortlisted products are shown in Figure 7. The annual theoretical **CO_2-binding volume** (column 3) was calculated by multiplying the total estimated EU production and import volume by the theoretical CO_2**-binding capacity** (column 2) per kg of product as per reaction. The **estimated retention time** (column 4) shows the number of years the CO_2 is approximately utilised in the given product (depending on its usage).

Methane and synthetic fuels have the highest CO_2-binding capacity in term of use volume per year. However, both of those products have a very low retention times, since the CO_2 is immediately released when the products are used. The highest retention time, approximately 50 years, is found for calcium carbonate. Although its total EU production and import volume is only about a tenth of the EU production and import volume of methane, the positive environmental impact is due to the long use potential resulting from its use as a building material. Polymers such as PP, PE, POM or PU have a moderate EU production and import volumes and an intermediate retention time (10 years). However, to fully understand and compare the environmental impacts of technologies and products detailed LCA must be conducted (see Section 2.3.2).

Methane has the largest potential annual CO_2-binding volume, due to its high production & import volume and a relatively high CO_2-binding capacity per kg of product. The market price of conventional methane, however, is fairly low and thus the production via CCU might not be a business case for producers, if no co-operation with producers of higher valued chemicals, such as polymers, is foreseen. Since the largest share (76%) of the European production and import volume is accounted for by imports, the CCU route could contribute to an increased independence from fossil resource imports and at the same time would not be a threat to domestic conventional methane producers.

Synthetic fuels also have a large CO_2-binding volume in the EU.[19] The product price is higher than the price of methane but still not competitive with the price of fossil fuels. The price of *Sunfire's* synthetic fuels derived from CO_2, for example, is double the benchmark price. When methane and synthetic fuels are used the CO_2 is relatively quickly released again after use. The theoretical CO_2-binding potential is about 1.5 Gt per year, and the yearly capture of CO_2 for their production could substantially contribute to mitigation. Given that most of these fuels will be used in transport, where the exhaust gas will not be used as an input for CCU processes, the contribution a circular carbon economy is limited.

Other products with a low retention time have a low total CO_2-binding potential due to their low European production volume. **Methanol** and **ethanol** both have a medium CO_2-binding capacity

19 No import data on diesel/kerosene fuels in the EU. If added, the total European market volume would increase.

per kg of product and have an annual EU production and import volumes of 8 Mt and 5 Mt respectively. The European methanol production and import volume is to a large extent served by imports, which means that here the CCU route could potentially contribute to an increased independence of methanol supply in Europe without competing with domestic methanol producers.

The **theoretical binding capacity for the EU** has been used as parameter for the screening, as a high binding volume indicates that the absolute carbon uptake of the produced goods could be high. Nevertheless, economic factors play a role and cannot be judged for the chemicals in isolation. Chemicals with large EU production and import volumes, such as methane, have a large potential binding volume, but the relative value generation per product is small. Products with a high value generation have a higher chance of reaching economic feasibility earlier, especially if they are based on CCU commodity chemicals; POM, for example, is based on CCU methanol that enters the value chain and can be sold for more than €2,000 per tonne. The additional costs for methanol production will be lower if compared to the price of POM instead of the price of methanol. The relative value generation was measured from product price only. Cost of production and margin could have been additional indicators, but determination for every product was not possible within the study.

The products with the highest binding capacities are methane, fuels and calcium carbonate for concrete substitution. Proteins show the highest relative value generation and the potential binding volume is average, hence proteins could be suitable for a competitive implementation of CCU.

All of the shortlisted polymers have an intermediate retention time (10 years). **Polyethylene** and **polypropylene** have a high CO_2-binding capacity per kg of product and a production & import volume of 2.3 Mt and 11.2 Mt, respectively. **Polyurethanes**, **polyoxymethylene** and **polycarbonates** together have a production & import volume in the EU of 1.6 Mt and their CO_2-binding capacities per kg product are relatively low.

The European production and import volume of **calcium carbonate** is 261.5 Mt annually. This mineralisation product uses the CO_2 for a long time (50 years). However, its CO_2-binding capacity per kg of product is relatively low. The European binding capacity adds up to 115.0 Mt of CO_2 annually. **Sodium carbonate** has a relatively low total binding capacity (2.0 Mt of CO_2) but may also use the CO_2 for several years, depending on the type of use.

To conclude with an overview of the estimated annual binding volume of all shortlisted CCU products by retention time, Table 5 summarises the total CO_2-binding volumes per year for each possible retention time. The vast majority (91%) of the annual binding potential only utilises CO_2 for a very short period of time (one year). These products are mainly used as fuel, energy products or intermediate chemicals. It is estimated that a total of 1.9 Gt of CO_2 could theoretically be utilised annually by the shortlisted CCU products if the total European production and imports were produced via the CCU route in an ideal system and the reactions were stoichiometric.

As will be shown below (see Section 2.3), the retention time is of less importance if CCU products replace fossil-based products, if the mitigation effect occurs during production of the products (cradle-to-gate).

Table 5: Total annual CO_2-binding volume and retention time of shortlisted products (estimate), in Mt

Retention Time (years)	
1	1,765
10	48
50	115
Total	**1,928**

Results of stakeholder survey regarding the readiness of specific technology applications (time to commercialisation and technical advancements necessary for large-scale demonstration)

Comparing this retention time with the average residence time of CO_2 in the atmosphere, which is well above 100 years,[20] the climate benefit of the temporary storage of CO_2 via CCU products is roughly comparable with the avoidance of some 10 Mt to 20 Mt of CO_2 emissions into the atmosphere.

As required in the terms of reference for this report, commercialisation criteria and conditions for economic viability, such as time to commercialisation, financial gaps and technical advancements necessary for large-scale demonstration, were queried in the stakeholder survey. The results show that conditions for market commercialisation economic feasibility vary greatly among different products and technologies, and are often indicated only vaguely.

The survey revealed that PtX and PtG products, such as fuels and chemicals for energy storage, are already at commercial technology maturity levels but commercialisation and economic viability strongly depend on regulatory and political frameworks. (5)[21]

Another interview partner producing fuels from direct air captured CO_2 estimated that their technology will become marketable in 2021, with costs depending greatly on plant size. To reduce technological and economic risks, large-scale production would be imperative. Currently the price for CO_2 fuels is higher than the conventional market price for products derived from crude oil. (10)[22]

A representative of a large industrial symbioses project producing various chemicals from CO_2-containing steel flue gas and hydrogen foresees commercialisation by 2030, with investment in excess of €100 million necessary, depending on the selected configuration. Current costs are above market prices, due to higher energy demands. (6)[23]

Another plant producing methanol from steel flue gas and variable energy will, according to the interviewee, be commercial in 2020, with an investment in plant costs of €50 million necessary.

[20] http://www.ipcc.ch/report/ar5/wg1/

[21] The names of participating companies have, to provide participant anonymity, been replaced by numbers referring to the questionnaire evaluation.

[22] The interviewee did not state a concrete financial gap. A 2017 ICCT report can serve as a reference. Here different scenarios give a necessary policy support of between €0.75 and €1.50 per litre (see pp. 17–19 in Christensen & Petrenko, CO_2-Based Synthetic Fuel: Assessment of Potential European Capacity and Environmental Performance. A report funded by the European Climate Foundation and the International Council on Clean Transportation. November 2017. https://www.theicct.org/sites/default/files/publications/CO2-based-synthetic-fuel-EU-assessment_ICCT-consultant-report_14112017_vF_2.pdf).

[23] No further details of how much above the market price final costs were given, since at the current state of the project the final product(s) are not yet defined.

In terms of pricing, CO_2 methanol is currently only competitive if renewable energy or hydrogen, as well as CO_2, are available at low cost and only on the existing European biofuel market with an energy price premium. (7)

A research and development consortium based around a cement producer is currently developing various chemicals from cement production flue gas, with a time to market ranging from 2 to 10 years, depending on the product. Products from non-hydrogenative routes are already considered commercial, while production routes with hydrogen still need a reduction in capital, as well as operating costs, of at least 50%. (8)

A representative of a company manufacturing polymers from CO_2 estimated the technology will be commercial in about five years, with an investment of €1 million to €3 million necessary for a small-scale demonstration plant. The main cost driver is capital investment rather than CO_2 or energy price. (11)

Overall, the information gathered in the stakeholder interviews does not allow for generalisation, due to its wide range and its dependency on the specific conditions for each application. As common issues though, the stakeholder consultation confirmed that for hydrogenate routes electrolysis for renewable hydrogen production at competitive costs as well as advancements in direct air capture of CO_2 are necessary technological advancements for the successful deployment of CCU technologies. Also, manufacturing scale-up and operational experience were identified as key for large-scale demonstration. Finally, it was stated that the markets and society would have to get accustomed to products derived from CO_2. (Convergence of opinion from all interviewees.)

Conclusion

Figure 8 shows the shortlisted products' estimated CO_2-binding volumes in the EU, calculated based on the annual European total production volume plus import volumes into the EU, dependent on the stoichiometric CO_2-binding capacity per kg of product. The bubble size indicates the retention time and the colour refers to the chemical route.

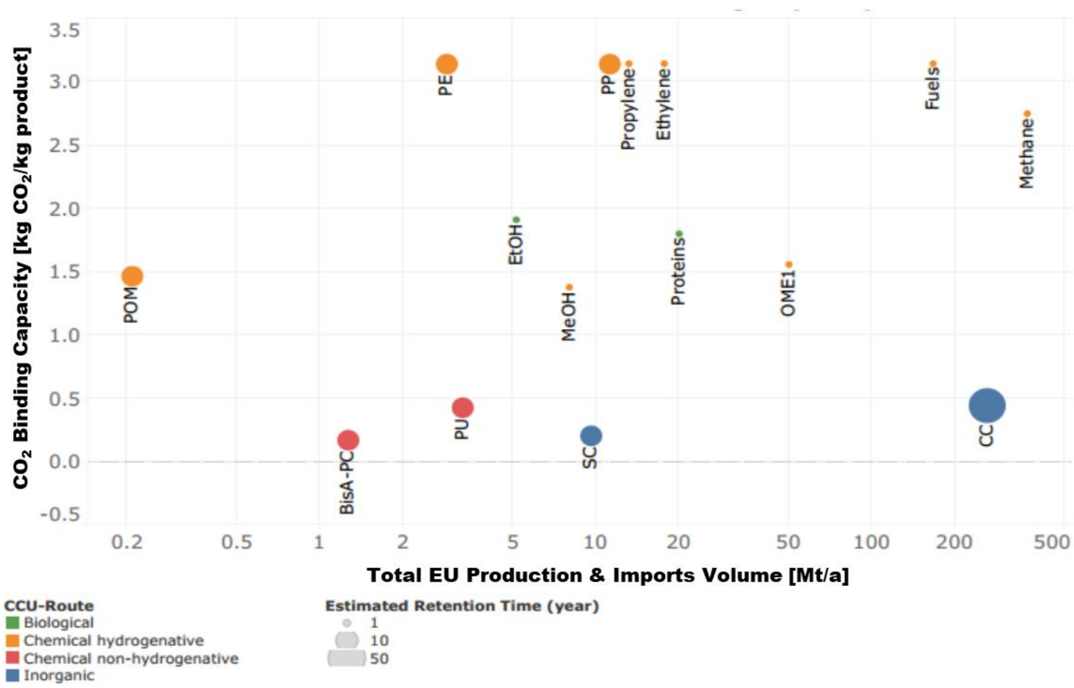


Figure 8: Total annual EU production & import volume, relative CO_2-binding capacity and retention time of shortlisted CCU routes[24]

The figure shows that while, for example, fuels and methane provide high binding capacities and high EU production and import volumes, their retention times are very low, while calcium carbonates provide a high volume and a long retention time, but a low binding capacity. PE and PP provide high binding capacities and intermediate retention times, but lower EU production and import volumes. Thus the figure points to the fact that among the promising CCU products a 'perfect fit' cannot be identified at the moment, i.e. a product made via CCU that simultaneously has a large potential market volume, a large CO_2-binding capacity and a long retention time and therefore could be considered the most promising regarding a possible emission reduction. Furthermore, one has to consider that the replacement of existing products by CCU products would not reduce carbon dioxide emission by the amount of CO_2 incorporated. Net savings of CO_2 can only be determined by a full life-cycle assessment.

It is important to note that Figure 8 *does not indicate technical, economic or environmental potentials* nor *any preferability*. It is necessary to consider the specific advantages and drawbacks, as well as trade-offs, of the specific CCU applications when assessing their potentials, whether technical feasibility, economic competitiveness or environmental performance. This would need to be clarified as a precondition of their eligibility for any funding support.

2.2.3 CCU technologies in a future ETS Innovation Fund

The aim of CCU technologies is the utilisation of carbon dioxide that would have otherwise been emitted. Thus, a potential emission reduction as the immediate ecological use of CCU technology applications and as a main selection criterion for an ETS Innovation Fund is evident. However, when assessing the eligibility of CCU routes for such future funding, other criteria might also be taken into account. The possible ecological advantages of CCU technologies are

24 Data based on shortlist (Appendix Section 4.2). Abbreviations according to list Table of abbreviations. Methane can also be derived by the 'Biological' route.

manifold and technology-specific, ranging from more efficient processes and a lower need for fossil materials to a possible overall net CO_2 emission reduction. Therefore a selection of the most apt technology applications for funding needs to combine and weigh different aspects and possible selection criteria.

2.2.3.1 Technical selection criteria

Selection depending on final product

As discussed above, CCU technologies can be applied in different industrial sectors. While specific applications vary in their characteristics, some overarching attributes of the sectors can be described. For example, regarding their potential market volume fuels produced with CCU technologies meet the largest volume of conventional fuels, but have only a very short retention time. The retention time would be longer with building materials or other minerals, but most of those are still in an early development state. With CCU applications for chemicals and plastics, the production & import volumes and retention times differ significantly and depend on the length of the use phase of the final product (e.g. mattresses approximately 7 to 10 years,[25] skiing boots approximately 7 years[26]).

These examples of attributes show that, generally, it is possible to differentiate between industry sectors regarding the CO_2 retention time within the product. Yet, an estimate of the retention time alone does not make possible a judgement about ecological worthwhileness, because, despite the later re-emission of utilised carbon dioxide, an ecological advantage in terms of an overall net emission reduction or avoidance and a contribution to decarbonisation efforts is possible and can provide eligibility for funding. For a given product portfolio the replacement of conventional products by CCU products will not affect the post-consumer CO_2 emissions. A mitigation effect can only be expected in the production phase.

Whether there will be a net GHG emission reduction can only be determined by a cradle-to-gate LCA.

Therefore a premature inclusion or exclusion of industrial sectors of CCU technologies depending on criteria such as retention time or life-time of CCU products does not seem advisable, while it would be possible to ascribe favourability regarding the overall attributes of a sector's products based on a cradle-to-gate LCA.

Selection via CCU routes

A CCU route, as described above, names a certain chemical reaction that results in a chemical product. These routes describe how CO_2 is converted into the given CCU product and in what form the energy for the reaction is provided (e.g. the hydrogenative route comprises reactions with hydrogen as a high-energy reactant). The routes do not describe the entire production process of a product made with CO_2, in which they are part of. Therefore they do not provide a sufficient basis for a selection for funding from an ETS Innovation Fund. Instead each entire upstream production process network has to be considered for funding needs, including the energy input related processes (such as renewable energy inputs), which is usually done via an LCA.

Readiness and innovativeness of a technology

[25] http://www.matratzenverband.de/Verbraucherportal/Tipps+zum+Matratzenkauf/Garantiezeiten/, accessed on 22 February 2018.

26 http://www.sportaktiv.com/de/skischuhe-fit-wie-nie, accessed on 22 February 2018.

As the selection criteria in this study reflect, technologies to be funded by an ETS Innovation Fund should not be commercially viable yet, but should be sufficiently mature for a demonstration at pre-commercial state and should be likely to reach at least TRL 7 by 2030. Nevertheless, in order to support profound and far reaching innovations, support for earlier development stages may also be considered for funding. Additionally, the innovativeness of a given approach should be taken into account. Innovativeness can, for example, be defined by the innovation content of a product (what is new?), the innovation intensity of the product (how new is the product?), the innovation subject (new to whom?) and the innovation state (often expressed in TRL). If the innovation is a process and not a product, its potential benefits should be reflected in the economic and ecological selection criteria.

2.2.3.2 Ecological effects as selection criteria

Selection via CO_2 emission reduction

The reduction of CO_2 emissions is the prime goal of all climate protection measures. Therefore, obviously, a main criterion for the selection of funding eligibility with regard to the Innovation Fund would be the net GHG emission balance. This balance would have to consider all CO_2 inputs, as well as CO_2 and other GHG emissions on a cradle-to-gate LCA to calculate the real carbon footprint of a certain CCU technology compared to a conventional technology (see below).

Global Warming Impact – GWI [measured in kg of CO_2 equivalent units / kg of product] is an environmental impact indicator to measure the potential effect on global warming based on the GWP (Global Warming Potential) of specific emissions, such as CO_2, methane and other greenhouse gases (GHG). GWP_i is the characterisation factor for the greenhouse gas i. GWI measures the resulting environmental impact. GWP_{100} values can be taken as a basis to calculate the respective global warming impact:

$$GWI = \sum_i emitted\ mass\ of\ GHG_i * GWP_i$$

In literature GWI is also referred to as GW (Global Warming) and calculated according to the same principle.

It should be noted that a net GHG balance of substitution of CCU products for conventional products requires a comparative LCA. Therefore a reference product needs to be determined, for which the LCA has to be conducted in the same way as for the CCU product.

Selection via resource efficiency

The EU aims to foster both climate protection and resource efficiency. The material resource efficiency of products can be determined with life-cycle-based indicators measuring raw material input or primary material requirements. **Raw Material Input (RMI)** measures the cumulative raw material inputs for the production of a product. It comprises abiotic and biotic materials. RMI accounts only for what is referred to as used extraction of raw materials. **Total Material Requirement (TMR)** includes, in addition to RMI, unused extraction (e.g. that part which becomes mining waste). TMR accounts for the total primary material which is extracted from nature for a product or service. Similarities to cumulative energy demand exist for TMR. TMR is thus the **most comprehensive material input indicator**, comprising all types of input flows, on a life-cycle-wide basis. RMI and TMR can be determined both for products as well as for whole economies.

As CCU technologies often require additional energy input and energy supply facilities require raw materials, those technologies may be associated with higher raw material inputs and higher primary material requirements. Based on comparative LCA a normalisation may be used to assess the resulting target conflict between climate and resource protection. Those technologies can be determined where the savings of GHG emissions are relatively higher than the additional amounts of material resources.

LCA: a method to integrate ecological selection criteria

Since many different ecologic factors can be taken into account when assessing the funding eligibility of a CCU project, it is of great importance to combine them in an integrated approach and to apply an objective and transparent assessment. A **standardised comparative life-cycle assessment (LCA)** for CCU products would be a viable approach for such an assessment. An LCA should be performed on a cradle-to-gate analysis (as a minimum requirement; cradle-to-grave would also be possible, but may be associated with higher costs without additional information).

Eligibility criteria for funding from the Innovation Fund could include that a comparative LCA between a CCU product and its conventional substitute proves a **minimum reduction of GHG emissions of, for instance, 20%**, and **does not lead to relatively higher specific contributions to raw material requirements**. The *relative proportion* of GHG emission reduction and higher raw material requirements would be determined by normalisation to determine the specific contributions: the difference values of Global Warming Impact and Raw Material Input between the CCU and conventional cradle-to-gate values are divided by their economy-wide values for the EU (or a Member State).

An LCA which provides the required information on ecological effects is advisable as a precondition for eligibility under a future ETS innovation fund. This kind of thorough assessment needs to be undertaken for each application individually. The ILCD Handbook General guide on LCA (2010) and several other publications (Jung et al., 2013; von der Assen et al., 2013; von der Assen et al., 2015) are already providing first guidance for a standardisation of LCA for CCU. Also, the Global CO_2 initiative is currently developing CCU-specific guidelines for LCA practitioners in an international project that will be available soon.

An advantage of using LCA methodology in assessing funding eligibility is that, depending on the scope of analysis (target questions, main issues to be considered), other ecologically relevant factors, such as **water footprint** or cumulative **energy demand**, can be included (please refer to Section 2.3 for details).

2.2.3.3 Other selection criteria

Selection via economic viability

To avoid the possible situation in which an application of a CCU route seems to provide an ecological advantage, but also is very costly (even in future scenarios) and thus is unlikely to be implemented in existing markets, it is also necessary to assess economic feasibility and competitiveness on the existing markets. A techno-economic assessment (TEA) is needed to determine the economic viability and competitiveness of a certain technology and can provide valuable guidance on process and business case development. The Global CO_2 initiative is currently developing, in an international project, CCU-specific guidelines for TEA practitioners which will be available soon.

Strategic fit of CCU technology applications with regard to EU policies as selection criterion

The implementation of CCU technologies might have reciprocal influences with different policies, such as, for example, in the field of energy generation or the production of fuels. Also, CCU applications that serve to store energy might have an impact on the further development of the energy system. Therefore it is important to avoid unwanted path-dependencies, for example the retro-fitting of coal-fired power plants, but rather to ensure the deployment of the positive impacts that CCU technologies might have.

A consideration for CCU under an ETS innovation fund and thus the fostering of CCU deployment can avoid counterproductive path-dependencies with European energy targets, since even ambitious environmental scenarios, e.g. (UBA, 2013), contain so-called 'unavoidable' residual emissions that would provide sufficient CO_2 to enable even a large-scale implementation of CCU technologies (see also Section 2.3.1 on CO_2 sources, Task 1.2, and Section 2.4.5 on path dependencies with energy policies, Task 1.3).

<u>Preconditions for all selection criteria: comparability and transparency</u>

While, for the time being, CCU technologies have not been incorporated under the ETS, in part due to their early development status, funding from an ETS Innovation Fund can be worthwhile if a preliminary ecological assessment is promising and points to possible contributions to a net reduction in CO_2 emissions, and economic feasibility and political compatibility are probable. Thus, ideally, the selection of CCU technologies for funding from the ETS Innovation Fund combines technical selection criteria, ecological viability, assessed by way of an LCA or other, life-cycle-based transparent and objective methodology, with economic feasibility, assessed with a TEA as well as the strategic political fit as described above. Only if an assessment of all three criteria comes to a positive conclusion can the proposed technical solution contribute sufficiently to reaching relevant EU targets and thus make it eligible for public funding.

In order to allow comparisons and transparency, technical, economic and ecologic assessments should be aligned to existing standards and guidelines.

2.2.4 Possible financing of CCU projects from EU financing programmes and instruments

In this Section a mapping of EU financing programmes and instruments is presented which identifies relevant programmes for funding CCU projects. This mapping focuses on current programmes in their form for the multi-annual financial framework period 2014–2020. In Task 2 a more forward-looking perspective is taken to look at how these programmes may evolve to adapt to the needs of CCU projects.

Aside from what the Innovation Fund is intended to provide, CCU projects may also be funded by other EU financing programmes and instruments, mainly under their respective objectives related to research and innovation, low-carbon energy and industrial processes, and climate mitigation. In the case of some programmes detailed further below funding may only be available for part of a CCU project (for example for the development of a renewable energy source supplying the CCU process' energy needs). Their eligibility for funding depends on each programme's eligibility criteria.

In the next few pages we describe individual EU financing programmes or instruments, including their relevant eligibility criteria, targeted sectors, and possible synergies.

2.2.4.1 Horizon 2020

The Horizon 2020 (H2020) programme offers grants, prizes[27] and financial instruments (such as the European Investment Bank's InnovFin Energy Demonstration Projects) for projects aiming at establishing new knowledge or exploring the feasibility of a new or improved technology (Research and Innovation Actions), and projects aiming at producing plans and arrangements or

[27] Horizon 2020 inducement prizes offer cash reward to CCU innovation under the Horizon 2020 CO_2 reuse prize worth €3.25 million.

designs for new, altered or improved projects, processes or services, including prototyping, piloting, large-scale product validation and market replication (Innovation Actions). In particular, H2020 targets the following activities relevant to CCU:

- reducing energy consumption and carbon footprint;
- low-cost, low-carbon electricity supply;
- alternative fuels and mobile energy sources;
- new knowledge and technologies; and
- market uptake of energy and ICT innovation.

Furthermore, the 2018–2020 work programme for secure, clean and efficient energy makes particular reference to addressing scientific and technological challenges related to CCU.

Due to the programme's objective of fostering cross-border co-operation, H2020 projects should involve at least three independent legal entities, each established in a different Member State or Associated Country.[28]

The European Investment Bank's **InnovFin Energy Demonstration Projects** (InnovFin EDP) is a programme that supports the transition of energy projects from demonstration to commercialisation with appropriate forms of finance.[29]

For the **InnovFin EDP** programme eligible projects need to be first-of-a-kind demonstration projects in the renewable energy, fuel cells or sustainable hydrogen sectors and can include first-of-a-kind power, head and/or fuel production plants and/or manufacturing plants. Project co-funding is offered in the form of grants of between €7.5 million and €75 million and targets projects that are typically too risky to access funding on affordable terms.

The InnovFin EDP programme should ensure contribution to de-risking the technologies and reassuring financial investors of their commercial viability, supporting the further rollout of innovative low-carbon energy technologies to the market and thus contributing to EU energy and environmental policies.[30] Projects or investments need to satisfy eligibility criteria for innovativeness, replicability, readiness for demonstration at scale, timeline, prospects for bankability and commitment of sponsors.[31]

Horizon 2020 funds the **Horizon Prize for CO_2 Reuse**, which has been established to reward innovative products utilising CO_2 that could significantly reduce the atmospheric emissions of CO_2 when deployed at a commercial scale.[32] Essential criteria for inclusion include that the innovations undertaken must result in genuine reductions in net CO_2 emissions from the relevant carbon dioxide utilisation technology/process. Based on the opinion of a jury, prizes are then awarded to the projects that best address a selection of cumulative criteria (i.e. net CO_2 emission reduction improvements based on prize-launch level (baseline) versus level of net CO_2

[28] European Commission, Horizon 2020 General Annexes.

[29] https://ec.europa.eu/research/evaluations/pdf/archive/other_reports_studies_and_documents/interim_evaluation_of_horizon_2020's_financial_instruments.pdf

[30] http://www.eib.org/attachments/thematic/innovfin_energy_demo_projects_en.pdf

[31] European Investment Bank, InnovFin Energy Demo Projects – Eligibility Questionnaire

[32] Novel carbon capture and utilisation technologies. *Group of Chief Scientific Advisors.* European Commission (2018).

emissions at final submission; overcoming barriers, including technical, commercial and financial; commercialisation and scalability; environmental impacts).[33]

The prize aims to support actors in the field of CO_2 utilisation with regard to accelerating their processes and product development, as well as to mobilise and enhance private R&I investment, attract non-traditional players, create new partnerships and motivate researchers and innovators to enhance efforts to abate emissions of anthropogenic CO_2 to atmosphere.[34] It ultimately addresses the issue of discovering the real potential of CO_2 utilisation to contribute to climate mitigation and of increasing transparency of technology readiness, barriers, costs, environmental performance and innovation needs.

2.2.4.2 Research Fund for Coal and Steel

The Research Fund for Coal and Steel (the RFCS) is a fund managed by the European Commission and funded by the European Coal and Steel Community. The RFCS supports research, pilot and demonstration projects in coal and steel sectors outside of projects funded by the EU's Framework Programmes.[35] It covers research on: production processes; application, utilisation and conversion of resources; environmental protection; and reduction of CO_2 emissions from coal use and steel production.[36] Article 6 of Council Decision 2008/376/EC, on 'Efficient protection of the environment and improvement of the use of coal as a clean energy source', and Article 8, on 'New and improved steelmaking and finishing techniques', in particular concern the reduction of coal and steel industry emissions and open the possibilities for funding of carbon capture, utilisation, and storage projects.

Participants in and beneficiaries of the RFCS can include 'any undertaking, public body, research organisation or higher or secondary education establishment, or other legal entity, including natural persons' in any EU Member State, candidate country or third country for the purpose of carrying out or supporting research and technology development activities, to the extent that the activities are in the interests of the EU.[37]

Project co-funding is offered in the form of grants. Access to RFCS funding is possible via its open and continuous call for proposals.

2.2.4.3 LIFE Climate Action

The LIFE Climate Action sub-programme has the objective of incentivising transitional change to a low carbon and climate resilient economy, in line with the 2020 climate and energy package and the EU's strategy on adaptation to climate change. In the context of the Climate Change Mitigation theme, co-finance grants are made available for best practice, pilot and demonstration projects contributing to the reduction of greenhouse gas emissions.

According to the LIFE Regulation the priority area 'Climate Change Mitigation' should contribute to the development and implementation of projects with regard to, inter alia, greenhouse gas monitoring and reporting, policies related to the emission trading system, carbon capture and storage, renewable energy technologies and energy efficiencies in areas such as industry,

[33] http://ec.europa.eu/research/horizonprize/index.cfm?prize=co2reuse

[34] https://ec.europa.eu/growth/tools-databases/eip-raw-materials/en/content/horizon-prize-co2-reuse

[35] Council Decision 2008/376/EC on the adoption of the Research Programme of the Research Fund for Coal and Steel and on the multiannual technical guidelines for this programme

[36] European Commission Resarch. http://ec.europa.eu/research/industrial_technologies/rfcs_about.html

[37] European Commission Resarch. http://ec.europa.eu/research/industrial_technologies/rfcs_about.html

services, buildings, transportation, lighting and equipment. The construction of carbon capture and storage infrastructure is considered beyond the scope of the LIFE Programme and is therefore not to be supported.[38]

Pursuant to Article 18 of the LIFE (2014–2020) Regulation action grants can be given for a variety of projects including, inter alia, pilot projects, demonstration projects, best practice projects, integrated projects, and preparatory projects.

Provided that the projects ensure net carbon emission reductions, the available funding may therefore, in principle, contribute to various components and needs of CCU projects, such as renewable energy provision, CO_2 emissions accounting, and introduction of CCU to industrial processes.

2.2.4.4 European Structural and Investment Funds (ESI Funds): European Regional Development Fund (ERDF) and Cohesion Fund (CF)

The ESI Funds' ERDF and CF[39] are the main EU investment policy tool supporting regional development through projects aiming at meeting EU objectives and regional development needs. Due to the ESI Funds' shared management mode,[40] specific eligibility criteria and selection process are dependent on a given region's Operational Programme and investment priorities agreed in concertation with the European Commission's Directorate-General for Regional Development.[41]

It should be noted that ESI Funds target public bodies rather than private sector. Any funding of CCU activities in industry must therefore adhere to regional aid guidelines.[42]

ESI Funds can contribute to projects in the fields of energy efficiency, renewable energy, smart grids, and energy infrastructure. ESI Fund allocations also include research and innovation into low-carbon technologies. The sustainable development principle (horizontal principle) ensures that considerations related to climate change mitigation are mainstreamed in all ESI Fund investments.

ESI Funds are driven by 11 investment priorities, also known as thematic objectives, of which TOs 1, 4, 6 and 7 are most relevant to CCU projects:

1. strengthening research, technological development and innovation;
4. supporting the shift towards a low-carbon economy in all sectors;
6. preserving and protecting the environment and promoting resource efficiency; and
7. promoting sustainable transport and removing bottlenecks in key network infrastructure.

[38] Regulation (EU) 1293/2013 of the European Parliament and of the Council of 11 December 2013 on the establishment of a Programme for the Environment and Climate Action (LIFE).

39 The ESIF is composed of five funds: the European Regional Development Fund (ERDF), the European Social Fund (ESF), the Cohesion Fund (CF), the European Agricultural Fund for Rural Development (EAFRD), and the European Maritime and Fisheries Fund (EMFF). Only the first two are, however, relevant to CCU.

40 https://ec.europa.eu/info/funding-tenders/how-eu-funding-works/management-eu-funding_en#differentmanagementmodes

41 http://ec.europa.eu/regional_policy/en/funding/accessing-funds/#3

42 European Commission, Guidelines on regional State aid for 2014–2020

ESI Funds require national co-financing from either public or private sources. The majority of EU funds are provided through grants; however, the ESI Fund policy framework emphasises the need for more use of financial instruments due to their leverage effect on EU funds, their capacity to combine different forms of public and private funds and because of their revolving form which facilitates more sustainable support in the long term.[43]

2.2.4.5 European Fund for Structural Investment

The European Fund for Structural Investment (the EFSI) is a risk-capital initiative launched jointly by the European Investment Bank (EIB) Group and the European Commission through guarantees from the EU budget and EIB funds. The ESFI is targeted towards overcoming the investment gap in the EU by mobilising private financing for strategic investments in key sectors, including strategic infrastructure such as: digital, transport and energy; education, research, development and innovation; expansion of renewable energy and resource efficiency; and support for smaller businesses and midcap companies.

The EFSI further supports projects which aim at: the use of renewable energy; energy efficiency and energy saving initiatives; and the development of infrastructure interconnections for energy.[44]

According to the EFSI Regulation in order to be eligible for EU support projects must:

- be economically viable according to a cost-benefit analysis performed in consistence with EU standards;
- be consistent with EU policies and the objectives of smart, sustainable and inclusive growth, quality job creation and economic, social and territorial cohesion;
- provide additionality;
- maximise where possible the mobilisation of private sector capital; and
- be technically viable.

Additionality, as defined in the EFSI Regulation, the support is directed to projects that address market failures or sub-optimal investment situations that would otherwise not be carried out. The projects must be economically viable and compatible with EU state aid rules and have a higher risk than EIB standard lending.[45]

2.2.4.6 Possible synergies between funds

Synergies between funds could be found in order to support CCU projects in different phases of development and implementation, or different parts of a project or multiple parallel projects (for instance renewable energy source and implementation of a CCU technology in an industrial process). In principle, all of the funds mentioned above can complement each other to fund projects.

43 Regulation (EU) 1303/2013 laying down common provisions on the European Regional Development Fund, the European Social Fund, the Cohesion Fund, the European Agricultural Fund for Rural Development and the European Maritime and Fisheries Fund and laying down general provisions on the European Regional Development Fund, the European Social Fund, the Cohesion Fund and the European Maritime and Fisheries Fund and repealing Council Regulation (EC) 1083/2006, preamble paragraph 34.

44 Regulation (EU) 2015/1017, Article 8.

45 Regulation (EU) 2015/1017, Article 5

From a project finance perspective, grants such as those under Horizon 2020 and LIFE tend to be more adapted to projects at the research and innovation stage. Financial instruments such as loans (from InnovFin and ESI Funds) are adapted to more advanced projects which are expected to generate revenue enabling the debt to be repaid. These projects may include deployment of proven CCU technology on industrial plants. More complex instruments, such as guarantees (from the EFSI), may also be considered to guarantee loans for a project with a high financial risk, thus leveraging of private finance.

2.2.4.7 Conclusion

To sum up, the current eligibility conditions of financing programmes and instruments under the multi-annual financial framework for the period 2014–2020 in principle offer opportunities for supporting CCU projects. These opportunities can be leveraged for CCU projects where those can potentially deliver benefits with regards to, inter alia, innovation, climate action, renewable energy, energy and resource efficiency, in line with the respective objectives of each programme.

2.2.5 Conclusions with regard to Task 1.1

The objective of Task 1.1 was to identify and select promising CCU technologies. As a result of the two-step multi-criteria assessment, as described in Sections 2.2.1 and 2.2.2, **15 promising CCU routes** were identified and screened with regard to their technical, economic and (a few selected) environmental aspects. In principle, these routes are eligible for further environmental assessment in Task 1.2 (Section 2.3 of this report).

Part of the multi-criteria screening was an **estimate of the theoretical annual CO_2-binding volume** of the shortlisted products, based on the binding potential of the specific chemical formula and the existing volumes of conventional products assuming their total replacement by CCU products. According to this estimate the total annual CO_2-binding of the shortlisted products would amount to 1,928 Mt of CO_2 per year (see Table 5).

The screening based on the aforementioned criteria is a viable approach for identifying promising CCU products and technologies based on their specific TRL and a following multi-criteria assessment. However, the **limited data availability** does not permit the making of a definitive statement on the economic volume of the products. In particular, confidential data, such as financial and cost figures, are generally available only in exceptional cases, and often not comparable, due to insufficient disclosure of assumptions. However, costs in relation to market price decide if a technology can survive on the market or if funding or subsidies are necessary. Also, economic, commercial and technology data is highly technology-specific and thus project-specific. Even if for one single project data is available, it cannot be generalised for all products, since economic and environmental data also depend on location, CO_2 input sources, energy supply, etc.

It must be emphasised that although this method is a viable 'traffic light' approach, the data compiled provides estimates in **'best case' scenarios in the sense of total replacement of conventional products by CCU products**. In order to make a definite statement on which products and technologies have the largest potential in terms of total emission reductions, a comprehensive LCA of the entire process, as well as a detailed market analysis, would have to be conducted. The environmental assessment of selected CCU technologies is described in Section 2.4.

A standardised life-cycle assessment (LCA) for CCU products and minimum GHG savings and minimum resource efficiency requirements compared to conventional technologies would be necessary preconditions for **possible eligibility under a future ETS innovation fund** and need to be undertaken for each application individually. The ILCD Handbook General guide on LCA (2010) and several other publications (Jung et al., 2013; von der Assen et al., 2013; von der Assen et al., 2015) and initiatives[46] already provide guidance or are preparing proposals for a standardisation of LCA for CCU.

With regard to other funding options, the current eligibility conditions of financing programmes and instruments under the multi-annual financial framework for the period 2014–2020 in principle offer opportunities for financing CCU projects. These opportunities can be leveraged for CCU projects where these can potentially deliver benefits with regards to, inter alia, innovation, climate action, renewable energy, energy and resource efficiency, in line with the respective objectives of each programme.

46 For example https://www.iass-potsdam.de/de/forschung/development-guidelines-techno-economic-analysis-tea-co2-conversion-processes

2.3 Task 1.2: Economic, climate and energy assessment

The purpose of Task 1.1 was to narrow down possible technologies to a shortlist of high potential and technically feasible processes. The objective of Task 1.2 was to determine economic preconditions for the implementation of CCU technologies and to assess environmental performance based on the potential reduction of global warming.

The following Section 2.3.2 thus elaborates on the most important common influences that will determine the economic feasibility of the implementation of CCU technologies. Sections 2.3.3 to 2.3.5 assess the environmental impact of certain CCU routes, which were selected from the technology shortlist.

2.3.1 Economic conditions for the application of CCU technologies

Economic conditions that can make a business case CCU technologies are manifold and to a great extent specific for each application. Nevertheless, some major common influences can be identified and elaborated on. CCU-specific, these are:

- availability and necessity of transport of CO_2;
- purity of available CO_2 and costs of CO_2 capture;
- pricing of CO_2 as a commodity and pricing of CO_2 emissions;
- availability and pricing of renewable energies;
- availability and pricing of fossil fuels, competitive products or import products;
- pricing of CCU (final) products; and
- potential dependency on other inputs and related infrastructures.

So as to elucidate external economic conditions influencing the competitiveness and implementation of CCU technologies this chapter will focus on two major factors that are of crucial importance to all CCU technologies:

- CO_2 sources, purity and benchmark costs; and
- availability and pricing of renewable energy, in relation to EU energy scenarios.

<u>CO_2 sources, purity and benchmark costs</u>

Although CO_2, from a global perspective, has become an undesirable flue gas in the context of anthropogenic climate change, it is a commodity good in some small-scale market segments that make use of the substance. In its industrial applications, in most cases, CO_2 is, however, only useful subject to the prerequisite that it is available in the highest possible concentration and degree of purity (Aresta & Dibenedetto, 2010). In some cases, however, impure CO_2 or gaseous mixtures can also be utilised. A wide range of technology is already available today for capture and treatment of CO_2 from natural and industrial sources, for example adsorption, absorption, cryogenic separation or membranes (de Coninck & Benson, 2014, p. 249). Consequently, the effort for capturing CO_2 depends on the source chosen in each case and on the technology used; the costs of capture can vary (see Table 6).

If industrial CO_2 emissions are compared, the processes in which highly pure CO_2 is emitted as a flue gas can generally be regarded as the most economical source. Such sources include, in particular, ammonia synthesis, hydrogen production, and natural gas extraction. During these processes, highly concentrated CO_2 occurs as a by-product which can be captured for less than approximately €35 per tonne of CO_2 (see Table 6 for benchmark costs). Some of these plants, therefore, already have CO_2 capture technology installed to satisfy existing demand. Thus a small proportion of these CO_2 emissions is already in industrial usage today. Moreover, biogas plants emit comparatively highly concentrated CO_2. These sources cause a total of around 300 Mt of CO_2 emissions annually (see Table 6).

CO_2 point sources which contribute the greatest share of emissions are fossil fuel power stations, which emit around 10 Gt of CO_2 annually (Naims, 2016). The installation of technologies for CO_2 capture is technically feasible at such large CO_2 point sources; however, it is associated with an average efficiency loss of around 10%–30% of the energy created at the power plant (de Coninck & Benson, 2014). Therefore CO_2 capture at power plants is not an economical option under current conditions and only exists in isolated cases at demonstration facilities. In modern plants, in particular as a result of economies of scale, comparatively low costs of capture of around €35 per tonne of CO_2 can be achieved (see Table 6).

Furthermore, other important industries, such as steel and cement production, emit large amounts of CO_2, around 3 Gt annually (see Table 6), which can be captured with the aid of various technologies. Depending on the quality and amount of capturable emissions and the loss of efficiency, the costs of capture vary.

In addition, what are referred to as 'natural sources' of CO_2 are able to provide CO_2 for utilisation too. These sources are primarily the natural extraction of CO_2 from rocks, oil and gas reserves and other naturally and durably saved CO_2 deposits. Due to their high CO_2 concentrations, the costs for extraction from these deposits are often comparatively low, at around €15–€20 per tonne of CO_2 (Aresta & Dibenedetto, 2010). Such extraction is therefore already carried out today, for economic reasons and on an unknown scale. Nevertheless, the extraction of CO_2 from the ground is contrary to the aim of removing CO_2 from the atmosphere with CCU. While it might be economically worthwhile, utilisation of CO_2 that is naturally locked in the ground should not be considered under any circumstances.

Capture of CO_2 from the air, also referred to as Direct Air Capture (DAC), is also already technically feasible today. However, due to the comparatively low CO_2 concentration, around 400 ppm (0.04%), it is associated with high energy requirements and therefore not yet an economic option other than for special indoor applications. In future scenarios in which high availability of cheap renewable energy is assumed capture of CO_2 from ambient air could become an interesting technological option.

Table 6: Potential sources of waste CO_2 (Naims, 2016)

CO_2 emitting source	**Global emissions** [a] (Mt CO_2/year)	**CO_2 content**[a] (vol%)	**Estimated** capture rate [b] (%)	**Capturable emissions** (Mt CO_2/year)	**Benchmark capture cost** [b] (€ (2014)/t CO_2) [rank]	**Groups of emitters**
coal to power	9,031 [c]	12–15	85	7,676	34 [6]	fossil-based power generation
natural gas to power	2,288 [c]	3–10 [d]	85	1,944	63 [9]	fossil-based power generation
cement production	2,000	14–33	85	1,700	68 [10]	industry large emitters

CO_2 emitting source	Global emissions [a] (Mt CO_2/year)	CO_2 content[a] (vol%)	Estimated capture rate [b] (%)	Capturable emissions (Mt CO_2/year)	Benchmark capture cost [b] (€ (2014)/t CO_2) [rank]	Groups of emitters
iron & steel production	1,000	15	50	500	40 [7]	industry large emitters
refineries [e]	850	3–13	40	340	99 [12]	industry large emitters
petroleum to power	765 [c]	3–8	not available	not available	not available	fossil-based power generation
ethylene production	260	12	90	234	63 [8]	industry large emitters
ammonia production	150	100	85	128	33 [5]	industry high purity
bioenergy [f]	73 [d]	3–8 [d]	90	66	26 [2]	high purity / power generation
hydrogen production [f]	54 [g]	70–90 [h]	85	46	30 [4]	industry high purity
natural gas production	50	5–70	85	43	30 [3]	industry high purity
waste combustion	60 [i]	20	not available	not available	not available	industry large emitters
fermentation of biomass [f]	18 [d]	100 [d]	100	18	10 [1]	industry high purity
aluminium production	8	<1 [k]	85	7	75 [11]	industry large emitters

Notes:

[a] Data from Wilcox (2012) if not indicated otherwise.

[b] See Table 2 for literature reference, assumptions and calculation methods.

[c] Data from IEA (2014, p. 113) based on the largest point sources suitable for capture and not including the emissions of the large amount of emissions that are caused by small decentral point sources in the mobility and residential sector.

[d] Data from Metz et al. (2005, p. 81).

[e] Refineries could include ammonia and hydrogen production. A separate listing is nevertheless interest to differentiate such high purity from general refinery CO_2 streams. The capturable emission data based on the estimated capture rates should ensure that emissions are not included twice.

[f] Undisclosed technological assumptions for emissions volumes and CO_2 content, if not indicated otherwise. For technological assumptions for cost data see Table 2. For bioenergy and fermentation emission estimates are only for North America and Brazil.

[g] Data from Mueller-Langer et al. (2007, p. 3798).

[h] Data for hydrogen from steam methane re-former from Kurokawa et al. (2011, p. 675).

[i] Data from Bogner et al. (2007, p. 596)

[k] Data from Jilvero et al. (2014) and Jordal et al. (2014).

Availability and pricing of renewable energy

The ecological worthwhileness of the implementation of CCU technologies and their economic feasibility also depends in many cases on the availability and competitive pricing of renewable energy. These are, in particular, all Power-to-X (PtX)[47] technologies (Mennicken et al., 2016; Olfe-Kräutlein et al., 2016; Piria et al., 2016; Sternberg & Bardow, 2015; Varone & Ferrari, 2015; von der Assen et al., 2016). Beyond the possible role that CCU technologies may play in fostering the energy supply transition towards renewable energy via improvement of energy storage options, CCU technologies in many cases can only prove environmentally viable if they are able to use cheap and renewable energy.

The EU Energy Roadmap for 2050 envisages a cut in greenhouse gas emissions of between 80% and 95%. To achieve this the power generation system would have to undergo structural changes and achieve a significant level of emission reduction by 2030 and by 2050, with about two thirds of energy coming from renewable resources (Roadmap, 2011).

The EU energy scenario for 2030 sets three major targets:[48] a 40% cut in greenhouse gas emissions compared to 1990 levels; renewables accounting for at least 27% of energy consumption, and at least a 27% saving of energy compared with the business-as-usual scenario. The target is to raise the share of renewable energy in the electricity sector to at least 45% by 2030. Energy system costs are expected to rise during the period to 2030 to a level of around 14% of GDP, compared to about 12.8% in 2010 (Commission, 2014b), and the costs of electricity and fossil fuels are expected to rise (Commission, 2014a). The Energy Roadmap also

[47] PtX technologies comprises of Power-to-Gas, Power-to-Liquids and Power-to-Chemicals.

[48] https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/2030-energy-strategy

predicts rising energy prices until 2030, but a subsequent decline or at least a delayed increase thereafter until 2050.

As the European Commission states, the 2050 energy scenarios are highly speculative and depend on many factors (Commission, 2011) Nevertheless, if the ambitious goals will be reached, it is assumed that a largely decarbonised energy system will deliver at least two thirds of its energy from renewable sources (Roadmap, 2011). From an efficiency perspective, it only makes sense to use energy from renewable sources for CCU processes if the electricity market (direct use of electricity without power storage) is saturated with renewable energy already. Only when more renewable power is produced than that required by the electricity market will the production of renewable hydrogen and associated CCU-based energy carriers make sense with regard to the larger energy market, including storage capacities (Piria et al., 2016). This perspective, however, does not take into account the material use of the CO_2, which can add additional value, combine energy storage with carbon recycling and, when looking both at sustainable energy and material supply, may prove to be more environmentally efficient than the storage of electricity for direct refeeding.

How do the EU energy scenarios relate to the economic reality of future CCU technologies?

While the detailed effects of the availability and pricing of renewable energy can vary for individual CCU routes, the overall effect on CCU technologies of the developments in the energy system seems rather clear: **the ecological feasibility of many technological options, in particular air capture and PtX, relies on the availability of renewable energy and the economic precondition will be its competitive pricing.** Thus a rise in energy prices of renewables will not foster the development of CCU technologies with their energy-intensive processes. On the other hand, rising prices for fossil fuels will make CCU options as replacement of carbon from fossil sources economically more interesting. Also, volatility in fossil fuel pricing can add to the attractiveness of CCU, as the replacement of imports with locally available CO_2 could provide additional independence.

2.3.2 Environmental framework for CCU

CO_2 capture options and available renewable energy

The following chapter gives an overview of the existing CO_2 sources in Europe and the spatial scenario for Germany. CCU locations with an increased emission reduction potential are shown. A spatial map from a promising region in northern Germany shows the regional availability of CO_2 sources and also the availability of renewable energy in the form of surplus power that is available at a respective distance from the CO_2 sources. The change of the viewing plane from Europe to a state in northern Germany illustrates that every region may have specific CCU preconditions that have to be met for CCU; if available, renewable energy should be used.

von der Assenet al. (2016) give a detailed overview on the variety of CO_2 sources and describe the individual attributes thereof, energy consumption for capture and the CO_2 concentration in the stream. The following map from their article depicts the available CO_2 sources for Europe and the spatial scenario in Germany for various branches of industry.

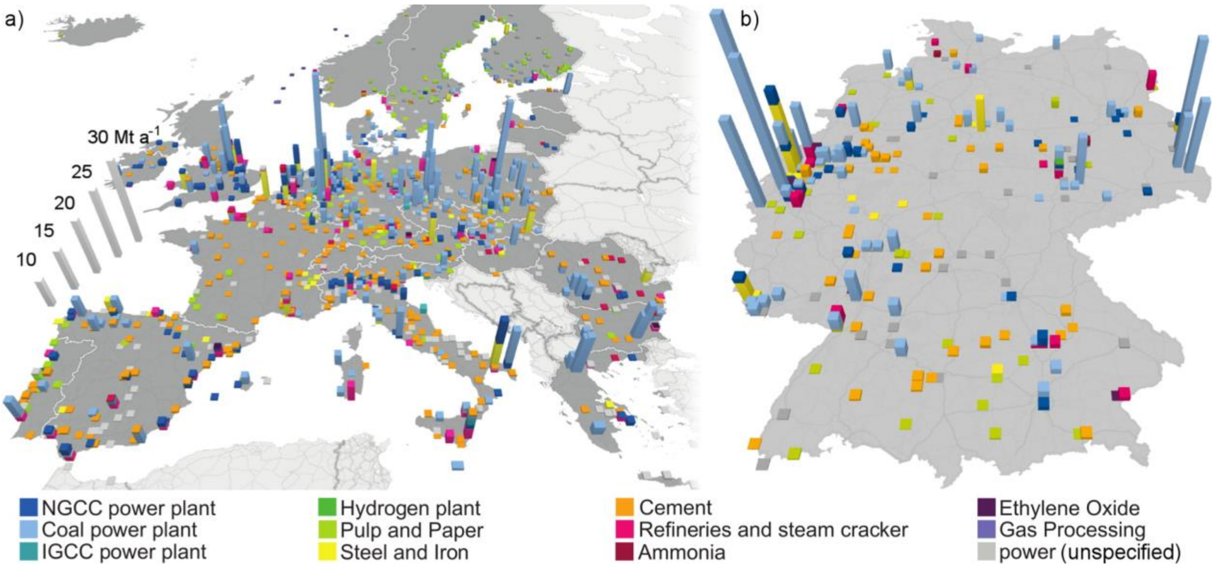


Figure 9: Distribution of CO_2 point sources (>0.1 Mt/a) in 2011 in a) Europe and b) Germany as an exemplary country. (von der Assenet al., 2016)
NGCC – Natural gas combined cycle, IGCC – Integrated gasification combined cycle

Potentially recycled CO_2 is not the only prerequisite for CCU application. Renewable energy has to be available in the region. Available energy can be expected in regions with a high share of renewable energy. Due to limited grid capacity it can be expected that certain surplus power may be available. In general, renewable energy is required to run CCU processes, but it competes with other uses and other storage options.

For Germany CO_2 is available from different point sources, as described in Hoppe et al (2017). The utilisation efficiency was identified to be high (0.9–0.95 tonne of CO_2 usable per tonne of captured CO). The following table gives an overview of available CO_2.

Table 7: CO_2 sources in Germany based on Hoppe et al. (2017) Sources: 1) German Biogas Association 2015; 2) VDZ e.V. 2015; 3) Statistik der Kohlenwirtschaft 2013; 4) BMUB 2012; 5) Götz et al., 2016 (yield of CO_2 per biogas plant); 6) VDZ 2013; 7) Icha 2015; 8) Urban 2007; 9) Spohn 2013; 10) ESRL 2016; 11) Bilitewski and Härdtle 2013; 12) IEA 2008; 13) Styring 2015.

CO_2 source	Number of plants	Amount of CO_2 emitted [Mt/a]	Concentration of CO_2 in the flue gas/mixture of gases/air [%]
Air	-	-	0.0401[10] (2015)
Biogas	8,726 (2014)[1]	75.55 (2014)[1, 5]	25–60[11]
Cement plant	55 (2014)[2]	18.84 (2012)[6]	25[12]
Lignite-fired power plant	48 (2015)[3]	163 (2013)[7]	10–15[13]
Waste incineration plant	73 (2012)[4]	16.51 (2009)[8, 9]	10–15[13]

The amount of emitted CO_2 from point sources in Germany is 274 Mt/a including coal and 110 Mt/a if coal is excluded. Assuming that 2.75 kg of CO_2 per kg of methane and 1.37 kg of CO_2 per kg of methanol can be transformed, Germany can transform the CO_2 to 100 Mt/a (40 Mt/a w/o coal) of methane or to 200 Mt/a (80 Mt/a w/o coal) of methanol. The conventional production of these chemicals for a material use for Germany is 360 kt/a of methane or 560 kt/a of methanol. The substitution from CCU products would require approximately 10 TWH/a for methane and 6 TWh/a for methanol. Based on a current annual production of 211 TWh[49] of renewable energy in Germany methane would require approximately 4.7% and methanol 2.8% of the total renewable energy. Curtailed, potentially available power is approximately 2.5% of the total renewable electricity production. Two and a half percent is less than enough to substitute either methanol or methane for the chemicals industry. Replacing the chemicals for the transport sector would require even more energy. Therefore available renewable energy is a limiting parameter for CCU if large amounts of electricity are needed.

The European perspective is not generally applicable for regional scenarios. Northern Germany will be used as a regional scenario, as the expectable emission reduction according to the approach of identifying beneficial regions for CCU is promising and the region is a major producer of wind energy in Germany with a high share of unused surplus power (see the chapter on energy supply scenarios for a detailed explanation). The following map shows CO_2 point sources and the available surplus power in Schleswig-Holstein, a state in northern Germany. **The only CO_2 sources shown are those which are close to either a wind farm where surplus power could be utilised or to the power grid through which regional surplus power could be used.** The sources are categorised according to the type of industrial source. The available renewable energy is depicted per local community and indicated as a share of the amount of generated electricity from wind farms. Surplus power is the amount of electricity that was not generated due to a shut-down of the wind turbines during times when the grid is overloaded.

[49] https://www.energy-charts.de/energy_pie.htm?year=2017

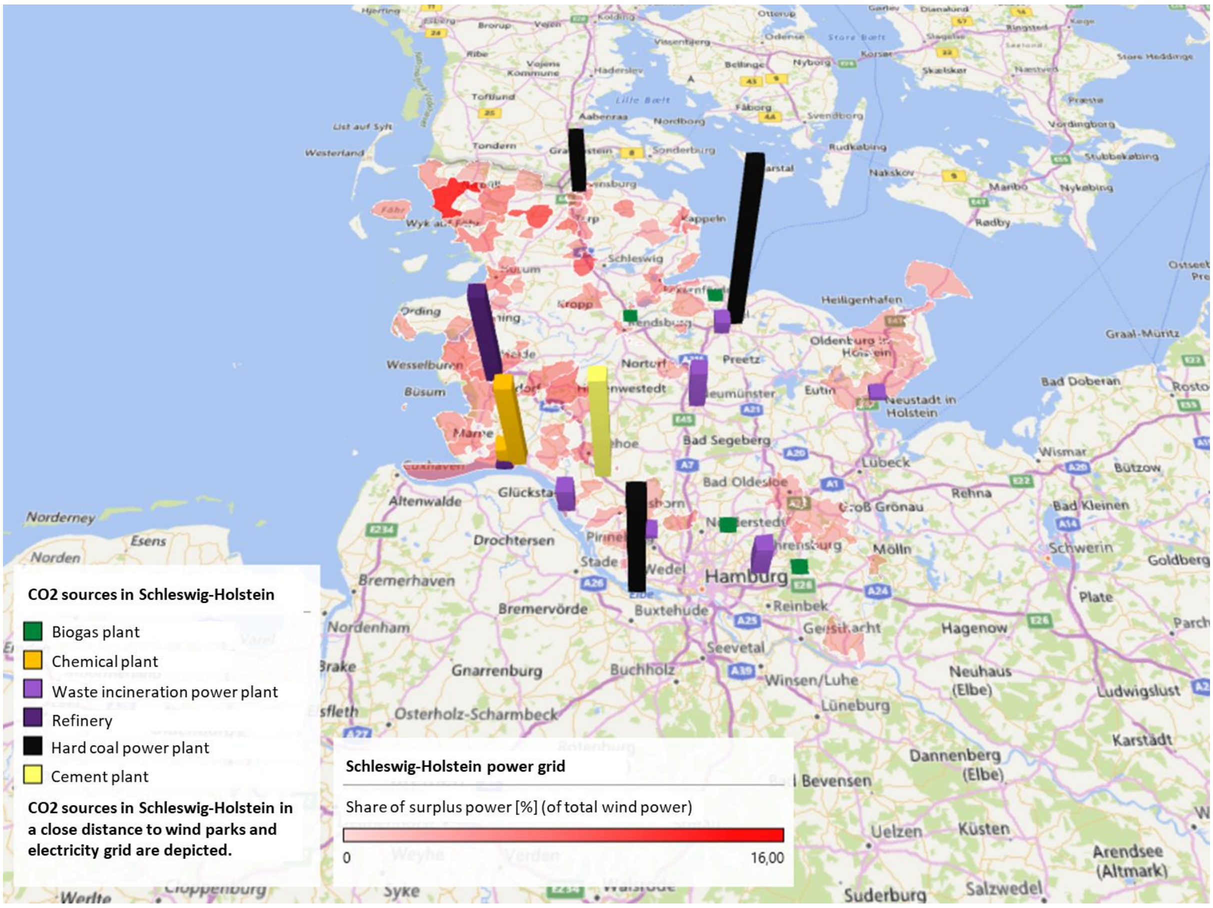


Figure 10: Regional map of Schleswig-Holstein in northern Germany indicating available surplus power from wind farms and CO_2 sources that can access the surplus power. Data was collected during the research for Hoppe (2018).

The largest CO_2 emitter in the east of the state has only limited access to surplus power. Other major emitters in the west are close to surplus power and hence show potential for the application of CCU technologies. The highest share of surplus power is found in the north-west, without a point source close by. The electrical energy would have to be stored and transferred to a respective CO_2 source, e.g. the hard coal power plant located to the east of the community. Considering that hard coal power plants' CO_2 emissions are expected to decrease in a regenerative energy future energy scenario, a more sustainable approach may be to focus on the three large sources (the cement plant, the chemicals plant and the waste incineration plant) in the centre of the map. It is shown that the availability of point sources and renewable power on a regional level is more complex than it seems on European or national scale. For the introduction of CCU locations need to be found that provide suitable options to integrate CO_2 capture, CCU product production and CCU product processing with the use of available renewable energy. Process integration and local networks in the sense of 'industrial symbiosis' would seem promising. Looking at other states in the south of Germany it cannot be expected that a similar amount of curtailed wind power is available, due to the lack of wind farms in the rest of the country. Solar power could provide electricity, but the overall availability may be different from in the north of Germany.

Looking at different regional levels within the EU shows that CCU might be developed primarily in regions with significant available renewable electrical energy. At the same time, relevant amounts of CCU chemicals may require more power than curtailed electricity could provide, so that regular renewable power would be required. In addition, locations where waste heat from industrial clusters could be used by process integration would be beneficial. **Co-operation between local networks of industrial symbiosis** may play an essential role in bringing together CO_2 providers, renewable power suppliers and CCU producers.

CCU as an energy storage technology

If renewable power needs to be stored, the efficiency of the storage technologies has to be considered (Sternberg et al., 2015). Electrical energy from renewable sources that is currently lost, such as surplus power, could be stored in a future energy system to increase the efficiency of energy generation. Different technological options exist and are being analysed in terms of their applicability and storage efficiency.

Mostert et al. (2018) evaluate the efficiency and the environmental impacts for a range of power storage systems, including hydrogen production (H_2-S) and synthetic natural gas (SNG-S). The results are shown in the following chart.

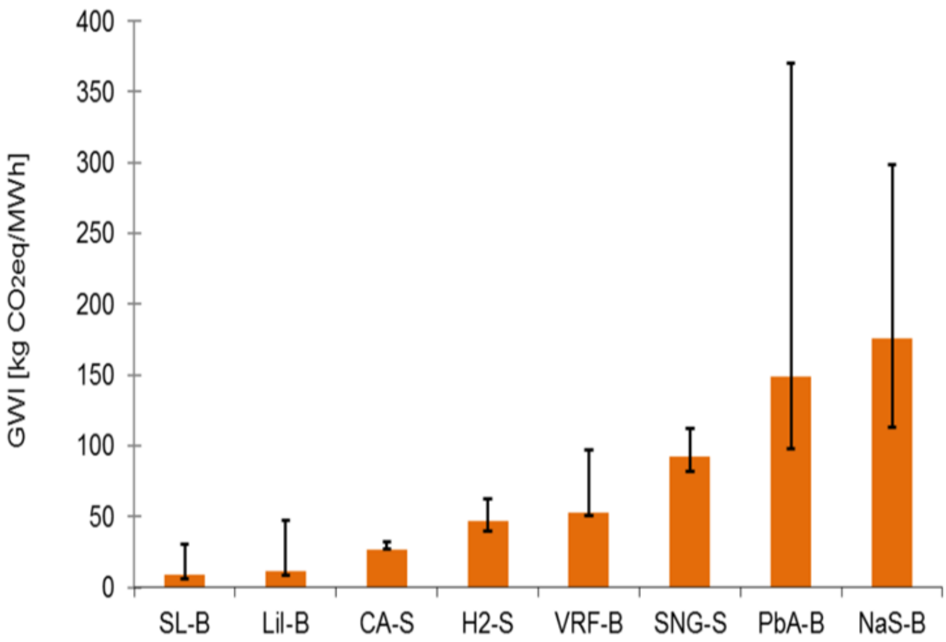


Figure 11: Global Warming Impact (GWI) v. fed-out electricity of electrical energy storage technologies (as described in Mostert et al., 2018)

Second-life batteries (SL-B) and lithium-ion batteries (LiI-B) have the lowest GWI per fed-out electricity with 9 and 11 kg CO_2eq MWh-1 (Fig. 2). They are followed by underwater compressed air energy storage (CA-S), power-to-gas storage using hydrogen (H_2-S) and vanadium redox flow batteries (VRF-B) with 27, 47 and 53 of CO_2eq / MWh. Power-to-gas storage using synthetic natural gas (SNG-S) has a GWI of 92 CO_2eq / MWh, nearly double H_2-S and 3.4 times CA-S. Lead-acid batteries (PbA-B) and sodium-sulphur batteries (NaS-B) have the highest GWI: 149 and 176 CO_2eq MWh-1. Their carbon footprint is 13.5 and 16.0 times higher than that of LiI-B.

The results indicate that other power storage technologies would be more climate beneficial than SNG. Synthetic natural gas could be produced via CCU. The results are comparable to Sternberg et al. (2015), where renewable energy use in lithium batteries, compressed air energy storage and heat pumps was found preferable to chemical energy storage in terms of storage efficiency.

The specific technical applicability for grid-balancing long-time energy storage is not considered, nor how products perform on a complete life-cycle basis. Both analyses follow the cradle-to-gate approach. Mostert et al. (2018) do consider the use and reuse phase of the storage systems, as well as the performance of second-life lithium batteries. End-of-life is not considered in either of the analyses.

Technological usability is a prerequisite for the use of the analysed energy storage technologies. While gasoline cars for short distance transport may be replaced by e-mobility, long-range transport by truck and ship and plane fuels, such as diesel, kerosene or diesel oils, are not yet replaceable. Carbon-based fuels can be used with the current state of technology and may present a solution with decreased environmental impacts compared to conventional production in combination with energy efficient technologies.

An inter-sectoral comparison for the utilisation of renewable energy in the transport sector to a chemical industry route could be a suitable approach for further research. The effects of the retention time for the use phase and the material and energy consumption in the respective recycling systems could be integrated to show for which route renewable energy can be utilised most efficiently and with minimum environmental impact.

Integration of CCU to the circular economy

The circular economy approach

The concept of the circular economy (CE) has been analysed by the Commission, the European Resource Efficiency Platform (the EREP), the Ellen MacArthur Foundation (the EMF) and the European Academies Science Advisory Council (EASAC, 2015). The current economic model is still, to a large extent, based on a linear process going from extraction of raw materials for production purposes to waste disposal of manufactured goods no longer used by consumers (take-make-consume-dispose). The Commission's vision (EC 2015) instead supports a 'transition to a more circular economy, where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised, and is an essential contribution to the EU's efforts to develop a sustainable, low carbon, resource efficient and competitive economy'. The key objectives of increased reuse, remanufacturing and recycling are an overall reduction of resources consumed and a reduction of environmental impacts (EMF, 2012; Club of Rome, 2015) (EASAC, 2016).

In recent years the concept of the circular economy was widened beyond the primary idea of recycling to take in the objective of resource efficiency in the sense of dematerialisation (CEC, 2015), which corresponds to the Reduce approach in the Japanese 3R policy (Reduce-Reuse-Recycle). Using less material and less primary resources is the most effective way to prevent the generation of waste. Seen at the same time are dematerialisation and 're-materialisation' complementary strategies, both of which contribute to a decoupling of economic growth and resource use and system-wide environmental impacts.

As pointed out by the EASAC in 2015, society's main goal in the circular economy is reducing the adverse interactions between the economy, the environment and its natural resources in order to safeguard the well-being of future generations, thus contributing to sustainability. Among the factors supporting a shift from a linear to circular economy are the following.

- Decoupling by using fewer resources per unit of economic output (resource decoupling) and reducing the environmental impact of any resources that are used (impact decoupling) are essential components of sustainable development (see Figure 12).

- The above considerations are particularly important for regions such as the EU which possess only scarce non-renewable resources and therefore depend on imports.
- Climate change: production and consumption patterns need to be sustainable in the long term, including with respect to greenhouse gas emissions, which have to be globally reduced to zero by 2050 to respect the 2 °C global warming threshold (UNFCCC, 2015).
- The environmental damage associated with resource extraction can be substantial. Since the basic objective of the circular economy is reducing consumption of natural resources, the associated environmental impact of resource extraction and waste disposal will also be reduced. The Commission also points out that environmental impacts have associated business risks through regulations aimed at restricting or pricing key resources (e.g. carbon pricing, water pricing, payments for ecosystem services, landfill taxes) which may also be reduced in a circular economy.
- An additional focus of the Commission's latest action plan is the role of the circular economy in green growth, innovation and job opportunities, which are not dependent on an unsustainable linear growth model. Such trends may also contribute to industrial competitiveness (see EASAC, 2015).

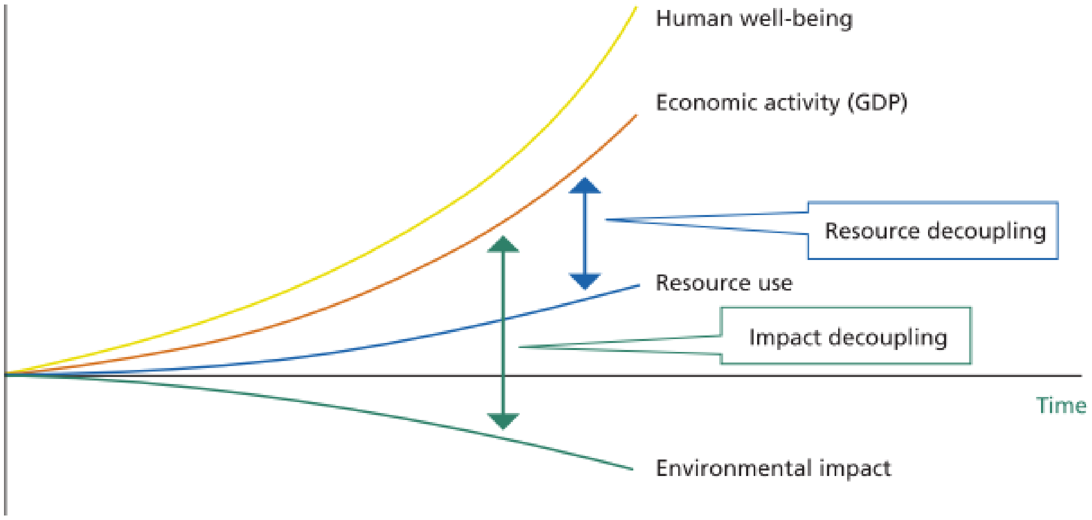


Figure 12: Decoupling resource and impacts (UNEP, 2011)

The Ellen MacArthur Foundation (2016) describes how the linear 'take, make, dispose' model, the dominant economic model of our time, relies on large quantities of easily accessible resources and energy. Besides efficiency increases, a shift towards technically renewable materials is also regarded as essential: the circular economy.

The concept of the circular economy has attracted attention in recent years. It is characterised as an economy that is restorative and regenerative by design and which aims to keep products, components and materials at their highest utility and value at all times, distinguishing between technical and biological cycles. It is conceived as a continuous positive development cycle that preserves and enhances natural capital, optimises resource yields and minimises system risks by managing finite stocks and renewable flows (EMF, 2016).

Integration of CCU in the circular economy

To date the chemicals industry has been supplied by natural gas, petroleum and coal, which are a source of both energy and carbon (Figure 13). The linear way of using these raw materials leads to CO_2 emissions into the atmosphere. In the future the energy supply will come from renewable resources and the carbon supply will increasingly rely on recycling (both of carbon-containing waste and CO_2).

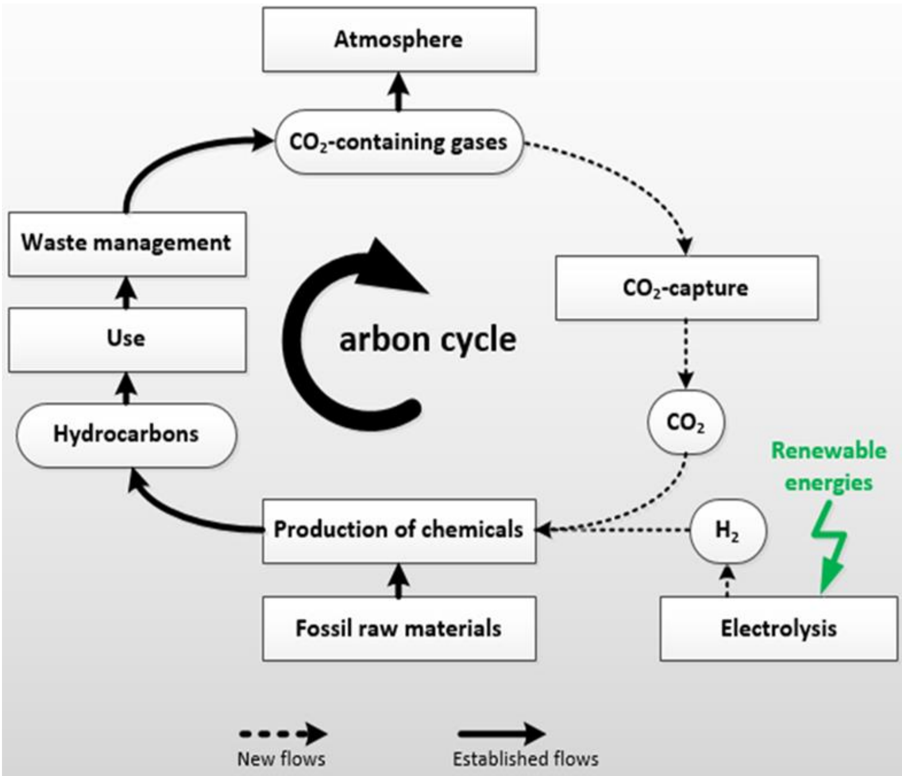


Figure 13: Scheme of future carbon recycling including CO_2 use driven by renewable energy (Hoppe, 2018)

The future circular carbon treatment with utilisation of chemical recycling, such as CCU, will be a circular approach with significant share of recycled carbon to replace fossil-based carbon. This will go hand in hand with a decoupling of the energy & material (carbon) supply which will enable the use of carbon as a raw material source. Carbon is mainly circulated, which decreases the amount of virgin fossil carbon added to the system. The processes for supplying renewable energy and for the production of CCU products will require infrastructure which in turn will depend on natural resource inputs. Therefore circular economy processes in general, and CCU technologies in particular, will require life-cycle-based consideration of the net benefits for climate and resources.

Chemical recycling via CCU offers new possibilities for waste management. CCU can replace landfill disposal and it can be used in combination with thermal treatment of waste to reduce emissions. Landfilling is still practised in some EU countries, but it is increasingly superseded by more advanced schemes of waste management, and it is already banned by 'zero waste-to-landfill' policies for organic waste, including plastics, in some European countries, such as

Norway and Germany. Different options for recycling of carbon-containing products are possible:[50]

- **Reuse and remanufacturing:** for example, wooden beams and furniture are reused, sometimes with processed surfaces.
- **Material recycling:** for example, separately collected or polymers of separated fractions from waste could be recycled into the same type of polymer (polyethylene to polyethylene, polypropylene to polypropylene).
- **Gasification or fermentation of C-containing wastes to chemical feedstock:** fermentation to biogas is widely practised for wet organic waste in the EU. Gasification is practised mostly for dry organic waste (currently mainly for industrial uses in Japan).
- **CO_2 capture from waste management or other sources to produce chemicals via CCU:** thermal treatment of mixed organic waste (in waste incinerators or cement plants) or fermentation to raw biogas, CO_2 capture and utilisation for new products with input of renewable energy.

These options complement each other. According to waste hierarchy principles, reuse and material recycling should generally be preferred to gasification, fermentation and CO_2 recycling. The main reason for that is that more energy is lost and the further waste products are broken down into their compounds and finally into CO_2. **CO_2 capture and utilisation is a recycling approach that widens the opportunities for recycling carbon-based chemicals or materials**.

Recycling processes consume energy, which may result in additional emissions of CO_2 if fossil sources are used. Moreover, infrastructure is required, which may lead to higher material resource inputs. Therefore it is necessary that the overall environmental benefit of recycling routes is determined on a system-wide (life-cycle-wide) basis, in order to introduce those technologies offering the greatest benefit.

Relevant indicators for monitoring the circular economy

The circular economy must meet the expectations for sustainable development in the same way as the economy as a whole. As a consequence, the basic set of indicators to measure the performance of the circular and linear economy at country or EU level remains the same.

Several monitoring concepts exist. EASAC (2016) lists the indicator sets shown in the following table:

Table 8: Indicator sets described in EASAC (2016)

Indicator set	Advocated by	Characteristic / data source	Number of indicators
Sustainable Development Indicators	UNEP	Major global environmental issues	10
Sustainable Development Goals	UNDP	Seventeen goals, such as ending poverty, fighting inequality and injustice, sustainable production and consumption, and tackling climate change	>250 (to achieve the 17 goals)

[50] This report focuses on the route of CO_2 capture and use only.

Corporate sustainability	Global reporting initiative (GRI)	Sustainability relevant indicators for organisations	>100
Environmental sustainability index (ESI); Environmental performance indicator	Yale and Columbia universities	Environmental indicators	21 (ESI) 20 (EPI)
Little green data-book	World Bank	Environment and sustainability	50
Green growth indicators	OECD	Environment, resources, economic and policy responses	25-30
Economic-wide material flow accounts (EW-MFA)	Eurostat Wuppertal Institute	Focused on material flows	6
Circular economy indicators	Ellen MacArthur Foundation (EMF)	Indicators currently available	7
Resource efficiency	EU Resource Efficiency scoreboard (EURES)	Eurostat, EEA and others	32
Raw materials	European Innovation partnership (EIP)	Raw Materials Scoreboard European union Raw Materials Knowledge Base (EURMKB)	24 4

Nevertheless, when it comes to specific indicators of the circular economy the following indicators are most relevant:

1. primary raw materials input;
2. final waste deposition;
3. post-consumer recycling rate; and
4. secondary recycling rate (or ‘recycled content’ as described in Graedel et al., 2011).

The effectiveness of the circular economy can be measured based on the reduction of primary raw materials and final waste deposition, as potential waste is recycled to secondary raw materials that replace primary raw materials. **A reduction of final waste deposits can only be achieved if the primary raw material input is reduced**. **CCU aims to reduce carbon-based primary material input by a reduction of waste CO_2.**

These indicators are increasingly being used at the Member State and EU level. It would also be helpful to know indicators (1) to (4) and GHG emissions at the sector level, for instance, for the chemicals industry as a whole. Thus the recycling rate of carbon and the secondary input of carbon could be monitored together with GHG emissions.

Recycling processes may cause additional GHG emissions or other environmental impacts, depending on the energy required and the type of energy use. Therefore it is important that recycling processes provide an environmental benefit both in terms of reduced resource consumption and reduced climate impacts. This will be further analysed for selected CCU routes in this study.

2.3.3 Selection of technological routes for LCA

This chapter describes which CCU processes from the technology shortlist (Section 2.2.2) were selected for a life-cycle assessment to determine the actual greenhouse gas reduction from production. Not all processes could be selected and modelled, therefore a representative selection of different processes was analysed to show the spectrum of possible CCU products. Available LCA data is presented and discussed according to the latest state of science.

The CCU processes for LCA were selected from the findings and the shortlist options generated in Task 1.1 as follows:

- Selected from the shortlist[51]
  - **Methane** via methanation
  - **Methanol** via direct hydrogenation
  - **Polyethylene** (PE) via a methanol-to-olefins process from methanol
  - **Polypropylene** (PP) via a methanol-to-olefins process from methanol
  - **Polyoxymethylene**[52] (POM) from conventionally produced methanol from CCU synthesis gas
- Additional data included
  - Synthesis gas via steam methane reforming
- Included based on available LCA data
  - **Polyurethane** via the Covestro process from polyols
  - **Synthetic Diesel** via the Sunfire process (Fischer-Tropsch and high temperature electrolysis)

We consider **methane**, as it is a key platform chemical for methanol and CO_2-based polymers. **Methanol** itself can be used for a large number of CO_2-based final products, including polymers (Benvenuto, 2014). Methane and methanol can be used as energy carriers as well as building blocks in the chemical industry. Synthesis gas is a building block and a necessary prerequisite for POM LCA modelling, due to the specific data set (see the database chapter in the Appendix). Market prices for methane and methanol are around €200 per tonne if ProdCom data is considered. The share of imported volume within the EU is for both chemicals above 75% of the production & import volume, thus a large part of the supply could be replaced without consequences for the intra-EU market. On the other hand, a dependency on fossil imports can be a signal that foreign producers are able to produce more competitively than the domestic suppliers. The market effects of widespread CCU application have to be modelled more comprehensively.

Synthesis gas is considered additionally to the shortlist, since it is an intermediate for methanol production from methane (Benvenuto 2014). In contrast to methanol and methane it can be used as an intermediate product only. It is part of many CCU production routes and

[51] Shortlist data can be found in the Appendix.

[52] In literature also known as Polyacetal or Polyformaldehyde.

conventional chemical processes, such as the Fischer-Tropsch synthesis, but in most cases it is produced on site and consumed immediately afterwards for further production. The evaluation of synthesis gas is additional to the selected technological routes and can be considered as an alternative production step to various CCU routes that can be evaluated in more detail in the future.

Polyethylene (PE) and **polypropylene** (PP) production is assessed, as they are among the polymers with highest demand in Europe (PlasticsEurope et al., 2012). Unlike these high-volume polymers, polyoxymethylene (POM) is a specialty polymer. Its advanced performance and price may facilitate the market entry of CO_2-based POM rather than large volume low price polymers. POM homopolymer is one of the polymers the carbon content of which could mostly be derived from CO_2 without any fossil raw materials.

PE and PP are commodity polymers with a cumulative production & import volume of more than 14 Mt. They can be recycled on a material basis or could be used to produce new chemical building blocks, such as synthesis gas (Lindner, 2015). The polymer keeps the CO_2 during the utilisation phase of its life-cycle, which has been estimated as approximately 10 years. A second life-cycle as, for example, material in the construction industry can extend the retention time, depending on the product it is used for. The overall market price of PE and PP is around five times higher than bulk chemicals; hence the potential to cover the costs for using CO_2 is higher than for bulk chemicals. The amount of CO_2 that can be incorporated in a kilogram of polymer is, at 3.1 kg per kg of product, among the highest on the shortlist. EU production from crude oil could be replaced based on methanol from CO_2, but crude-oil-based ethylene and propylene are produced within the EU in a multi-product process also yielding gasoline, diesel and various oils. A reduction in conventional ethylene and propylene production may affect the production of other products. If process technology is not adapted, a substitution of selected crude oil products would need to replace all products from multi-product process crude oil distillation in an equal proportion. This also means that products such as ethylen/propylen and diesel production would have to be replaced. A more thorough analysis of the technological options and consequences of replacing selected product streams from crude oil distillation seems necessary.

POM is an engineering thermoplastic and specialty polymer with application options in the industry. Similarly to PE and PP, the life-cycle was classified as 10 years. After the utilisation phase reuse and material recycling are possible (Lindner, 2015). Reuse, or mechanical recycling, requires less energy than material recycling of the CO_2 via CCU and prolongs the life-cycle duration by another 10 years, with potential of further looping. With a market price of €2,780 per tonne, POM generates the second highest value of all materials on the shortlist, which leaves a high potential for covering the initial chemical recycling costs for the CO_2 molecule. The binding capacity is similar to methanol, but lower than for methane, PE and PP. EU production from methanol could be replaced based on methanol from CO_2. Due to the high share of imported methanol displacement effects within the EU are negligible. POM has the potential to replace other plastics not producible via CCU in their material function, but, due to the high price, the current production & import volume of POM is relatively small (0.2 Mt).

CO_2 used as feedstock is a relevant input flow. Therefore the system boundaries include all upstream processes of feedstock CO_2, starting at the CO_2 source. General source characteristics are: (a) non-biogenic point sources; (b) biogenic point sources; and (c) air capture. The LCA includes cement factories and lignite-fired power plants as an example for (a), biogas plants for (b) and air capture for (c). Additionally, waste-incineration plants belonging to (a), but usually containing fractions of (b), will be studied. Both (a) and (b) generate a main product while CO_2 is a by-product. The purpose of (c) is to provide CO_2 as a product. The performance of carbon capture depends on process conditions, such as available heat, CO_2 purity and others.

The production of **polyols as a material to produce polyurethane** is discussed in von der Assen & Bardow (2014), who analysed the production using LCA. Polypropylene is used as a raw material together with CO_2. The integration of the CO_2 in the production enables the replacing of some of the conventional carbon source with the CO2 low energy molecule. The overall energy input of the process is reduced. Furthermore, electricity is produced, which can be used to further reduce the carbon footprint. The LCA shows that the environmental performance could even be increased if all raw materials used were to be produced from recycled carbon. Although the resulting product price is relatively high, the CO_2-incorporating polyurethane is being produced and put on the market.

An LCA for the Sunfire process for production of **synthetic diesel** is available from the University of Stuttgart (2015) and will be described in the literature review. We assume that the product of Sunfire is comparable to conventional diesel, as the LCA does not indicate the exact chemical composition of the product. The production is analysed using different electricity sources as well as optional use of waste heat. Air capture and a lignite-fired power plant are potential CO_2 sources. The performance of the Sunfire process is expected to be somewhere in between the compared results. CCU diesel production is compared to the production of conventional diesel, as well as to the production of biofuels, in megajoules, as these products are solely fuels.

We considered a selection of technological routes for CCU processes for organic chemicals and polymers. They are representative with regard to their role as commodity base chemicals and final polymers. Energy carriers, as well as building block chemicals, are covered by methane and methanol. Commodity materials with a retention time of 10 years and with a high specific CO_2 input are covered in the form of PE and PP. High value materials with a 10-year retention time and good potential recyclability are represented by POM. All process routes are suited to future chemical carbon recycling. While those process routes are based on hydrogenation and electrolysis (and would therefore need to be combined with renewable energy supply), the CO_2 use in the production of polyurethanes by Covestro represents an energy efficiency enhancement (and thus does not need additional energy, instead saving energy).

In the following, we have not further considered Bis-A polycarbonates. Although they may represent promising future polymers, direct incorporation of CO_2 in the product is limited, and further inclusion of CCU-based educts needs further research. Ethylene and Propylene are a part of PE and PP production, the difference of conventional PE/PP to the respective CCU processes is caused by CCU ethylene or propylene production. PE and PP are based on these commodity chemicals, but were chosen as they show a larger value generation. Mono-oxymethyl ether shows a reasonable performance in the shortlist screening, but production data for an LCA is not available and the production is completely based on methanol.

The mineralisation process, especially the production of calcium carbonate as a cement substitute, is a further option for CCU that should be considered based on the high EU production volume identified in the shortlist. Only a few LCA for mineralisation processes with additional mining are available in the literature, which is likewise stated as a research result in the CO_2U Roadmap by ICEF (2017). The most recent LCA for the reaction of CO_2 and the mineral serpentine will be presented in a separate Section (state of technology for mineralisation with additional mining, p. 109). The results are not valid for calcium carbonate mineralisation without additional mining, but can be used as an initial estimation for an example mineralisation process. The technological routes are manifold and under development, but no sufficient LCA data was available for calcium carbonate production. The results of the desk research for mineralisation technologies will be summarised and presented as the last part of the environmental assessment. LCA data for mineralisation routes without additional mining was available only for magnesium carbonate and alkaline waste-water. LCA data for carbon curing processes was not available.

Production of proteins from algae represents a high value option, as the proteins can be sold with the highest price identified in the shortlist. The EU demand is still small, but the demand for carbon-neutral animal feed may increase in the future. LCA data was not available. LCA data was also not available for the Steelanol process, where CO_2 from steel production is used for the biological production of ethanol.

2.3.4 Life-cycle assessment for selected processes

The methodology of LCA is described in the IPCC Guidelines for National Greenhouse Gas Inventories (2006) and in the ILCD Handbook – General guide on LCA (2010) and internationally standardised in ISO 14040:2006 and ISO 14044:2006. ISO 14040:2006 and ISO 14044:2006 describe the principles and framework for LCA and will be used as a methodological foundation for the LCA in this study.

The life-cycle assessment is based on Hoppe et al. (2017) and the results of an upcoming publication by Hoppe (2018). A detailed introduction and methods chapter including data basis and Life-cycle Inventory, as well the supporting information, can be found in the Appendix (in Section 4.3.5 Additions to Life Cycle Assessment) of this report.

The scope for this LCA is to evaluate environmental impacts and to identify GWI reduction potential for the selection of technological routes using a comparative approach and cut-off LCA models with background data from ecoinvent 3.1.

The used system boundary is depicted in the following Figure 14.

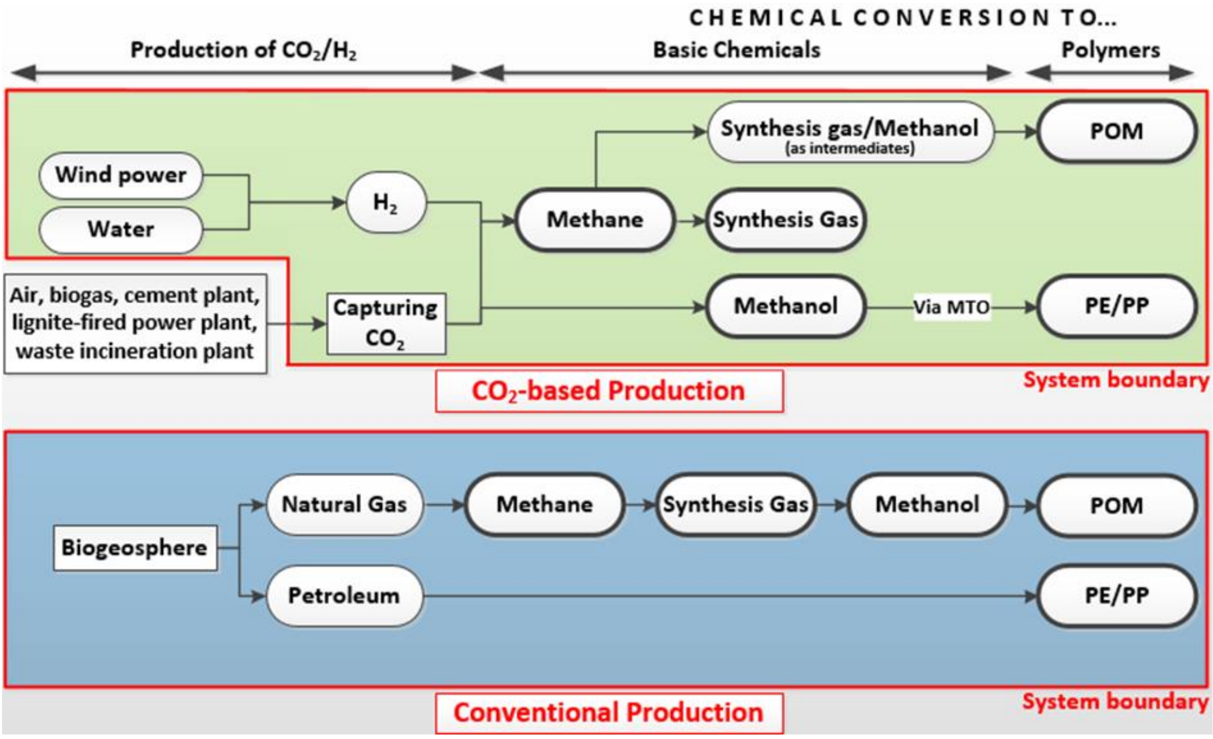


Figure 14: System boundary of the analysed routes of CO_2-based and conventional production (relevant products are circled in bold). Capturing from the respective source and electrolysis (H_2 production) from renewable wind power are included in the analysis (Hoppe et al., 2017).

We analysed the production of methane, methanol, and synthesis gas as basic chemicals and derived polyoxymethylene, polyethylene and polypropylene as polymers by calculating the output-oriented indicator *global warming impact* (GWI) and the resource-based indicators *raw material input* (RMI) and *total material requirement* (TMR), as well as the *cumulative energy demand* (CED) and the water input balance on a cradle-to-gate basis. As a carbon source we analysed the capturing of CO_2 from air, raw biogas, cement plants, lignite-fired power plants and municipal-waste incineration plants. Wind power serves as an energy source for hydrogen production. Our data was derived from both industrial processes and process simulations. Different scenarios were evaluated to find favourable transport routes, first inter-sectoral use analysis or the break-even share of renewable electricity to achieve environmental impact reduction. Individual heat sources for capturing are described in the Appendix (in table A1). The capture process from a cement plant is assumed to utilise a high share of waste heat and can be used as a benchmark for CCU performance if waste heat can be utilised.

We compared GWI, RMI and TMR, CED and water consumption of conventional and CO_2-based chemicals derived from different CO_2 sources. The choice is made in consideration of the four footprints concept developed by Steinmann et al. (2016) indicating that indicators for carbon footprint, material footprint, water footprint and land footprint account for more than 80% of the variation of LCA impact indicators. Using this insight we reduced the number of indicators to the minimum necessary without reducing the reliability of the study. Land footprint has not been analysed for CCU processes. We have included CED, as it is a general LCA indicator that is well known and accepted. RMI, TMR and CED are input-oriented indicators for accumulated raw material and energy demands. They serve the function of a control indicator to see whether an emission reduction is achieved via an increased material or energy consumption. The water input for CCU production was accounted for the production chain. A spatial attribution of those processes would be necessary in subsequent analysis to assess whether the water input would be critical with regard to water availability in producing regions (e.g. in water-scarce regions, such as the Mediterranean).

Results of the life-cycle assessment

The results for the different indicators are listed in the following Section. A cross-product comparison, for instance, methane versus methanol, is not intended and would be hampered by the fact that the functional unit (kg) does not reflect the different properties of the chemicals. Nevertheless, combining the results for the different products in those figures makes it possible to visualise how the indicators change along the production chain from platform chemicals to polymers.

Global warming Impact

Global Warming Impact – GWI [measured in kg CO_2 equivalent units / kg product] is an environmental impact indicator to measure the potential effect on global warming based on the GWP (Global Warming Potential) of specific emissions such as CO_2, methane and other greenhouse gases (GHG). GWP_i is the characterisation factor for the greenhouse gas i. GWI measures the resulting environmental impact. GWP_{100} values can be taken as a basis to calculate the respective global warming impact:

Relation of GHG. GWP and GWI:

$$GWI = \sum_i emitted\ mass\ of\ GHG_i * GWP_i$$

In literature GWI is also referred to as GW (Global Warming) and calculated according to the same principle.

It should be noted that a net GHG balance of substitution of CCU products for conventional products requires a comparative LCA. Therefore a reference product needs to be determined, for which the LCA has to be conducted in the same way as the CCU product.

The CO_2-based basic chemicals produced with wind-powered electrolysis have a lower GWI than the conventional ones (Figure 15). The highest GHG savings for methane and synthesis gas production occur if CO_2 is captured from cement plants. Producing methanol from CO_2 captured either from waste incineration or cement plants shows the biggest differences in terms of GWI compared to conventional production. The production of PE and PP via CO_2 captured from point sources would be more favourable than the conventional processes. The alternative CO_2-based routes have nearly similar performance, with waste incineration and cement kilns as the most favourable carbon sources. In contrast, the DAC routes for PE and PP would emit even more GHG, due to the excessive heat and electricity demand. All alternative processing routes of POM production show lower GWI compared to the conventional route. The route via CO_2 captured at cement plants again reflects the lowest impact. The difference between the alternative routes and the conventional pathways is rather low. This is due to the low input of CO_2 per kg of POM.

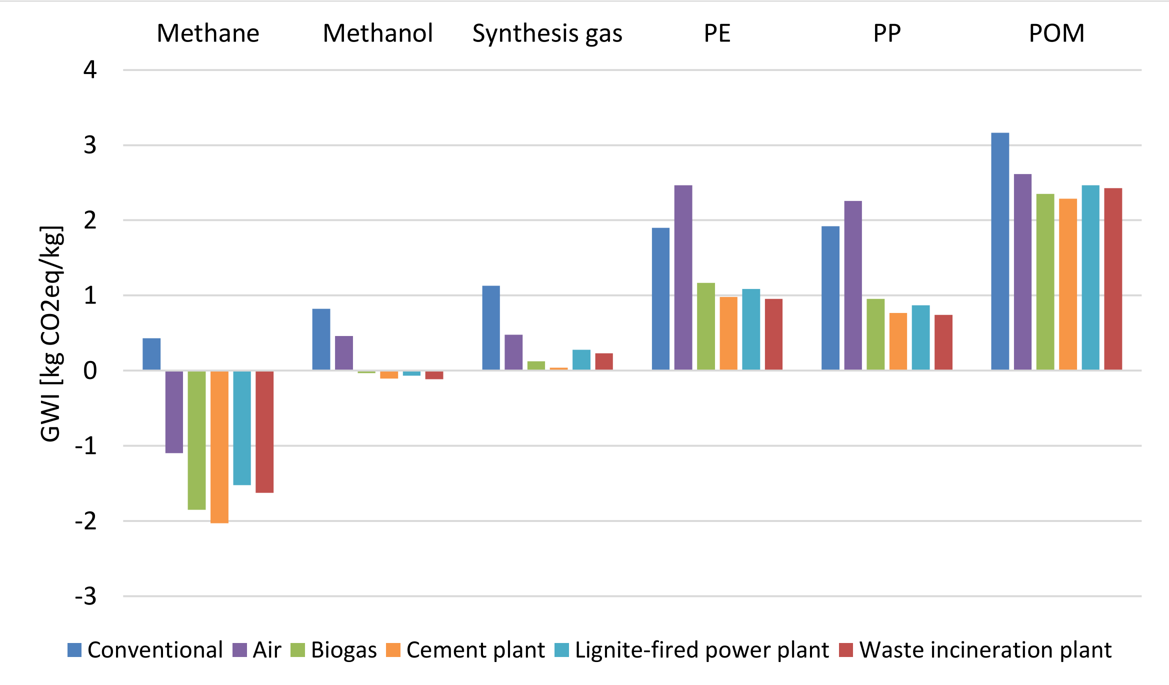
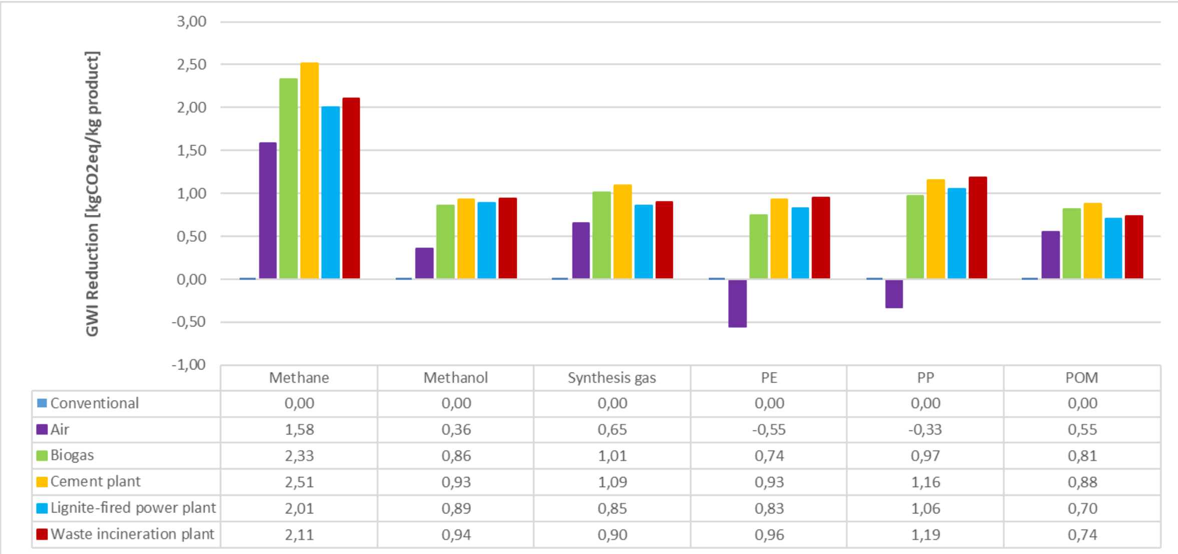


Figure 15: GWI for production of basic chemicals and polymers from different CO_2 sources compared to the conventional method (Hoppe et al., 2017)

The actual decrease in global warming impacts is the amount of CO_2 input that is not emitted by the CCU process compared to the conventional process. Figure 16 shows the **difference in GWI**. The amount of reduction is taken as zero reference for the conventional processes. Replacing a conventional process with another conventional process of the same kind does not achieve improvement. However, a more efficient conventional process may yield environmental impact reductions if compared to the standard. In this study conventional process improvements have not been considered. In general, production from cement plants, waste incineration and biogas plants gives the highest GWI reduction potential. Direct air capture performs worst, for PE/PP it would cause an increase in GWP. In general DAC has a high demand for heat, which could be covered by waste heat where applicable. Except PE/PP production from DAC, all CO_2 sources and all production routes show the potential to reduce GWI. Methane has a very high potential compared to the others, as the carbon content in the molecule is relatively high compared to methanol.



	Methane	Methanol	Synthesis gas	PE	PP	POM
Conventional	0,00	0,00	0,00	0,00	0,00	0,00
Air	1,58	0,36	0,65	-0,55	-0,33	0,55
Biogas	2,33	0,86	1,01	0,74	0,97	0,81
Cement plant	2,51	0,93	1,09	0,93	1,16	0,88
Lignite-fired power plant	2,01	0,89	0,85	0,83	1,06	0,70
Waste incineration plant	2,11	0,94	0,90	0,96	1,19	0,74

Figure 16: GWI reduction potential for the production of basic chemicals and polymers from different CO_2 sources compared to the conventional method (based on Hoppe et al., 2017)

A calculation of the GWI based on GWP_{100} demonstrates the effects of the retention time on the specific products. The ILCD Handbook (2010) describes the calculation of GWP_{100} for different life-times of products containing carbon which would be emitted after the use phase (e.g. by incineration). The same chapter (ILCD 2010, p. 226 ff.) recommends not using it in an LCA unless explicitly required. One shortcoming is certainly the assumed linearity of the GWI.

Nevertheless, an example has been calculated to show the effect of the retention time based on CCU product groups (see Figure 17). We assume POM to have retention times classified as below 1 year, about 10 years, 50 years, and 100 years. We show the GWI based on $\mathbf{GWP_{100}}$ for the conventional products and the CCU substitutes with the respective assumed retention time. The relative amount of reduction is applicable to all products, POM has been used as an example.

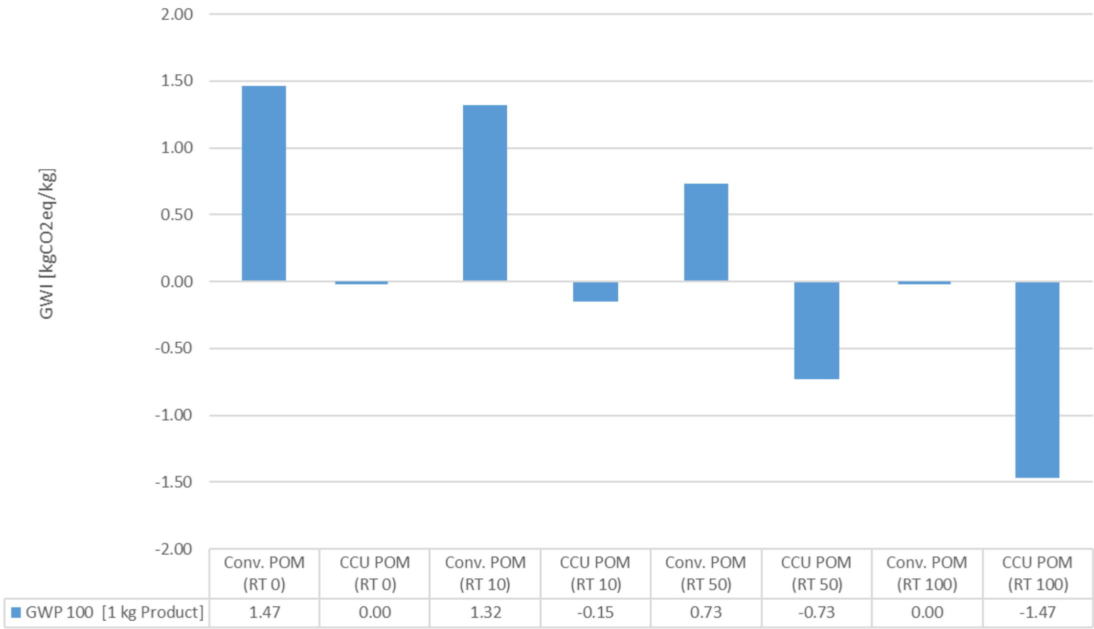


Figure 17: GWI based on GWP_{100} values for conventional and CCU POM assuming different retention times (based on the ILCD Handbook, 2010)

Conventional POM with a retention time of below one year would emit its content in the form of 1.46 kg of CO_2 per kg (e.g. by incineration of the waste). This amount of fossil-based CO_2 would directly start to be climate active and be so for the next 100 years. CCU POM utilises the same amount of CO_2 for its production, hence the GWP_{100} is balanced to 0. Both materials are described as RT 0, as the retention time is one year or below. There is no emission bonus. The calculated amount of emitted CO_2 is decreased within the 100-year span by 1% for every year the CO_2 is bound in the product, therefore **both products** (conventional and CCU) get a bonus for each year of retention time. The RT 50-year materials get a bonus that is equal to 50% of the total emission. The conventional POM would have 50% less emissions to be accounted for and the substituted POM would even have a negative balance. For the 100-year retention time conventional POM would have zero emissions, while CCU POM would have a negative climate impacts of –1.46 kg of CO_2 per kg. The difference between conventional and CCU POM **remains the same** as the recycled CO_2 is used for the production phase.

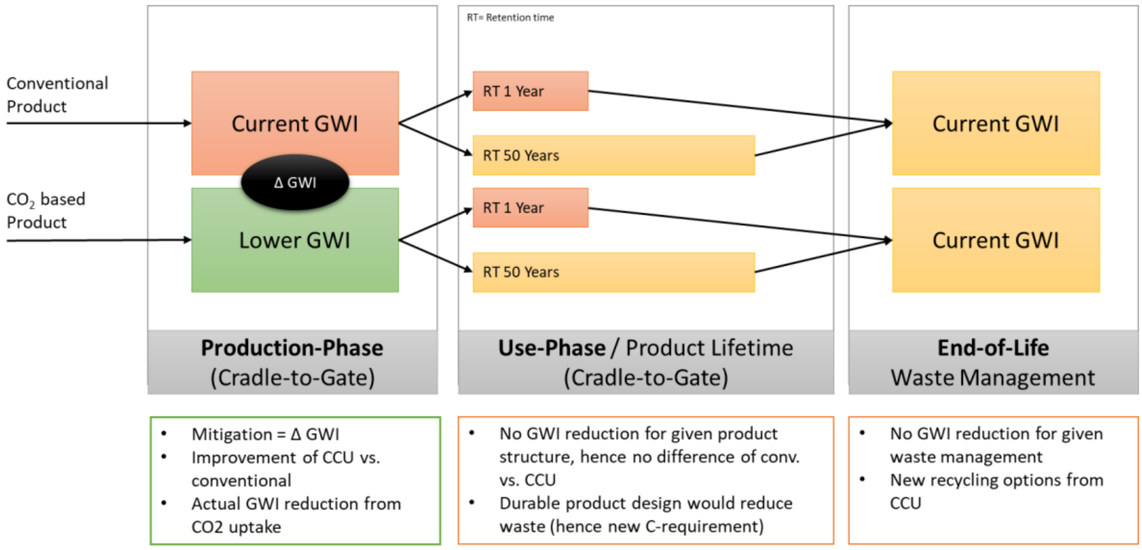


Figure 18: Summary of the effects of CCU to the production, use and end-of-life phases for the conventional and the CO_2-based product life-cycle

Figure 18 summarises the effects of the CCU approach for carbon recycling conventional and CO_2-based product chains. The production phase can be improved by reducing the global warming impacts by way of a more sustainable production with actual CO_2 uptake. Use phase and end-of-life phase are similar for conventional and CO_2-based products. More sustainable product use can lead to environmental impact reduction and a CCU-as-recycling approach can be the key to close the carbon cycle.

When assessing the mitigation effect of CO_2 use technologies it is important that these effects occur in the production phase (cradle-to-gate) and are independent of the way the products are further used (assuming that CO_2-based products replace conventional products). The retention time of carbon during the life-time of products may be influenced by changing product design and consumer preferences, but that would be relevant for both conventional and CCU products. The retention time of carbon in products, i.e. their life-time, does not affect the CO_2 mitigation effects during production.

GWI reduction potential for the EU has been estimated and listed. Further results can be found in Section 4.3.4 of the Appendix: Global warming reduction potentials for the European Union. As an example, CCU methanol using CO_2 from a waste incineration power plant (WIPP) is shown. It is assumed that different shares of the current production & import volume of conventional methanol are replaced by CO_2-based methanol. The GWI reduction shows by how much the CO_2 emissions could be theoretically reduced by the substitution. The amount of renewable energy required is indicated assuming that the demand for electrical energy of the capture, electrolyser and methanol synthesis would be covered by renewable electricity. All electrical energy for the operation is considered, not for manufacturing of, for example, process equipment. The share of EU GWI shows the maximum which could be reduced given the respective share of EU production. The limiting parameter is expected to be available renewable electrical energy: 1,258 TWh/a in 2020 based on the EU having a 34.5% share renewable electricity of 3,645 TWh total electricity production, as assumed in the 'Current Policies Incentive' scenario of the Energy Roadmap 2050 (European Union, 2011).

Table 9: GWI reduction, electrical energy demand for the replacement of EU conventional by CO_2-based methanol

Substitution-Scenario	Share of EU Production & Imports	Methanol [Mt/a]	GWI Reduction [Mt/a]	Required REN electrical energy for production [GWh/a]	Share of EU GWP (Eurostat 2018)	Substitution-Scenario
Domestic EU production	15%	1.21	1.13	14.29	0.03%	Domestic EU production
Half EU production & imports	50%	4.02	3.78	47.64	0.09%	Half EU production & imports
Imports to EU	85%	6.83	6.42	80.99	0.15%	Imports to EU
Full EU production & imports	100%	8.04	7.56	95.29	0.17%	Full EU production & imports

Raw Material Input and Total Material Requirement

The EU aims to foster both climate protection and resource efficiency. The material resource efficiency of products can be determined by life-cycle-based indicators measuring raw material input or primary material requirements. **Raw Material Input (RMI)** measures the cumulative raw material inputs for the production of a product. It comprises abiotic and biotic materials. RMI accounts only for what is referred to as extraction of raw materials. **Total Material Requirement (TMR)** includes, in addition to RMI, unused extraction (e.g. that part which becomes mining waste). TMR accounts for the total primary material which is used for a product or service. Similarities to cumulative energy demand exist for TMR. TMR is thus the **most comprehensive material input indicator**, comprising all types of input flows, on a life-cycle-wide basis. RMI and TMR can be determined both for products as well as for whole economies. A comprehensive description for the latter approach can be found in Eurostat (2013). For the application at the (CCU) product level, see Hoppe et al. (2017). Background information on the rationale is provided by Bringezu & Bleischwitz (2009).

Input indicators complement output-oriented indicators, such as GWI. If alternative process routes require more material resources than conventional ones, the related environmental impacts, for instance mining and subsequent disposal, will increase, especially if large material quantities are extracted for material use or energy consumption.

As CCU technologies often require additional energy input and energy supply facilities require raw materials, those technologies may be associated with higher raw material inputs and higher primary material requirements. Based on comparative LCA, a normalisation may be used to assess the resulting target conflict between climate and resource protection. Those technologies can be determined where the savings of GHG emissions are relatively higher than the additional amounts of material resources.

In terms of the input-oriented indicator RMI, a different picture to that from GWI reduction appears. The total material intensity of conventionally produced basic chemicals and polymers is lower than the total material intensity of their CO_2-based alternatives. The route via CO_2 from cement plants shows the lowest total material intensity of all CO_2-based production methods. The results shown contain both the abiotic and biotic parts of RMI and of TMR. As the biotic amounts are negligible, (below 0.1 kg/kg for all cases) no visual distinction was made in the following figures.

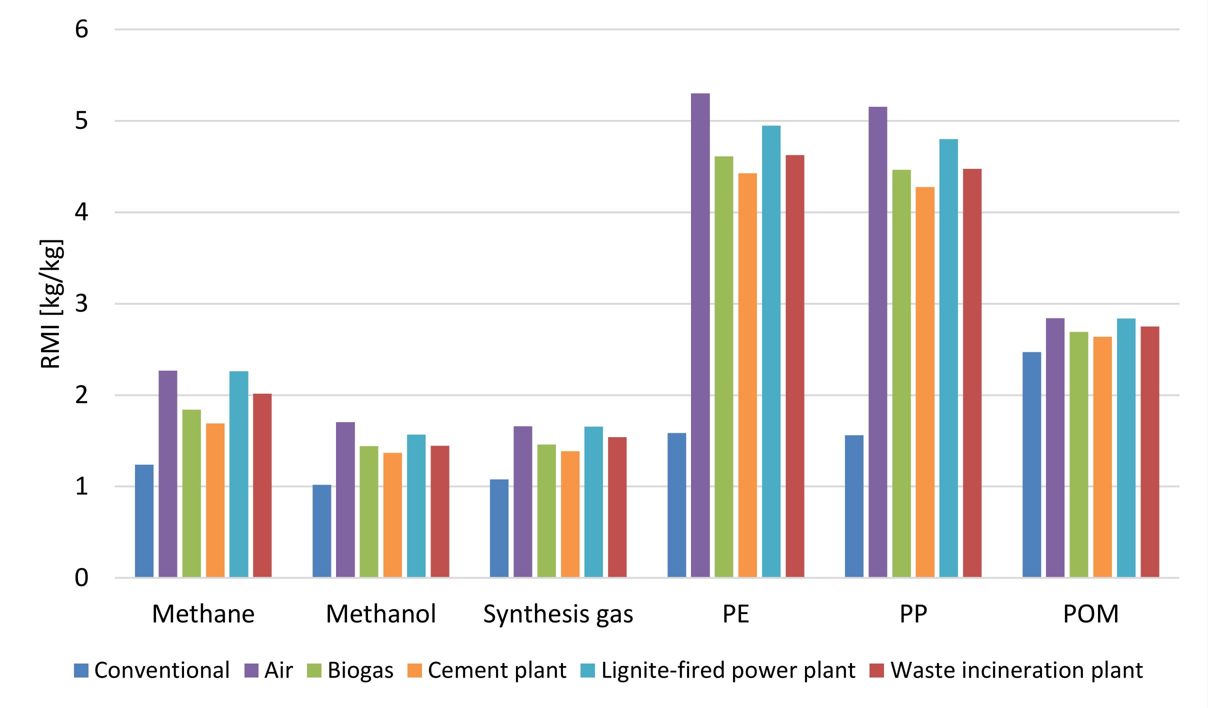


Figure 19: RMI for production of basic chemicals and polymers from different CO_2 sources compared to conventional methods (Hoppe et al., 2017)

The same pattern results for TMR (Figure 20), although with higher values, as TMR includes RMI. Conventionally produced basic chemicals and polymers have the lowest TMR. Again, CO_2-capture via cement plants has the lowest material intensity in all process chains.

The higher material resource requirements for the studied CO_2-based products result mainly from the high energy demand of the electrolysis process. The power for this process is provided by additional infrastructure, such as wind turbines (which require, for example, copper in the generator). Although wind power has the lowest material intensity per kWh of all power generating technologies currently used, the high energy demand of the CCU processes leads to high cumulative raw material requirements.

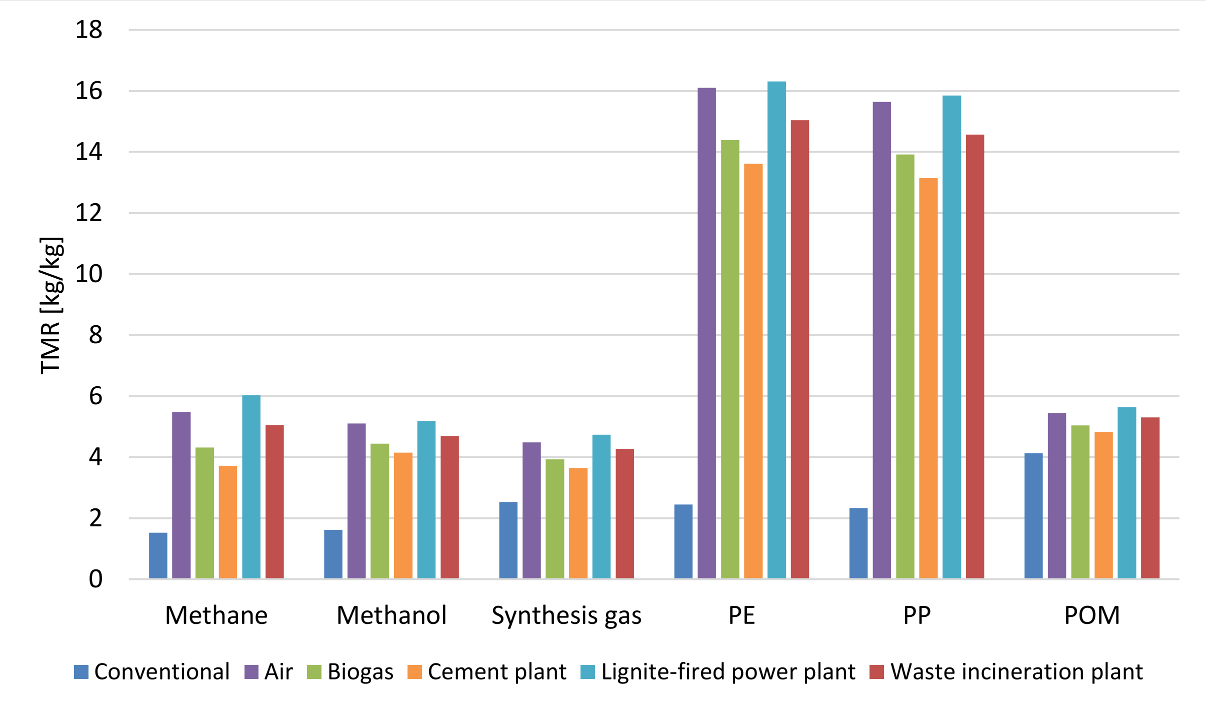


Figure 20: TMR for production of basic chemicals and polymers from different CO_2-sources compared to conventional methods (Hoppe et al., 2017)

Normalisation of raw material intensity vs. GWI

For assessing the trade-off between GHG emissions (GWI) and raw material input (RMI), a normalisation was conducted to compare the savings in GWI vs the increase in material consumption. We normalised the results for GWI and RMI with data for the European Union.

We used the following values for the European economy: GWI $4.4 * 10^{12}$ kg of CO_2eq in 2015 (Eurostat 2018) and RMI $9.7 * 10^{12}$ kg in 2015 (Eurostat 2017). No current TMR data for the EU was available. The most recent TMR data was for 2007 (GWS 2011).

Setting the difference values between conventional and CO_2-based products in relation to the European order of magnitude of those indicators shows the proportional extent to which those environmental pressures are changed. As a result, **GWI savings for the production of basic chemicals and POM are relatively higher than the additional pressure from RMI**. Considering PE and PP, the increase of material intensity based on RMI is relatively higher than the savings in GWI. For PE normalised GWI is $-2.15 * 10^{-13}$ and RMI is $3.13 * 10^{-13}$. Normalised GWI for PP is $-2.68 * 10^{-13}$ and RMI is $3.00 * 10^{-13}$. The difference for PP is smaller than for PE, but still both processes require more material input in comparison to the reduced GWI. The different performance of PE and PP is caused by the energy-intensive MTO-process as part of the CO_2-based process chain. Other process technologies producing these olefins on a CO_2-basis may offer better performance.

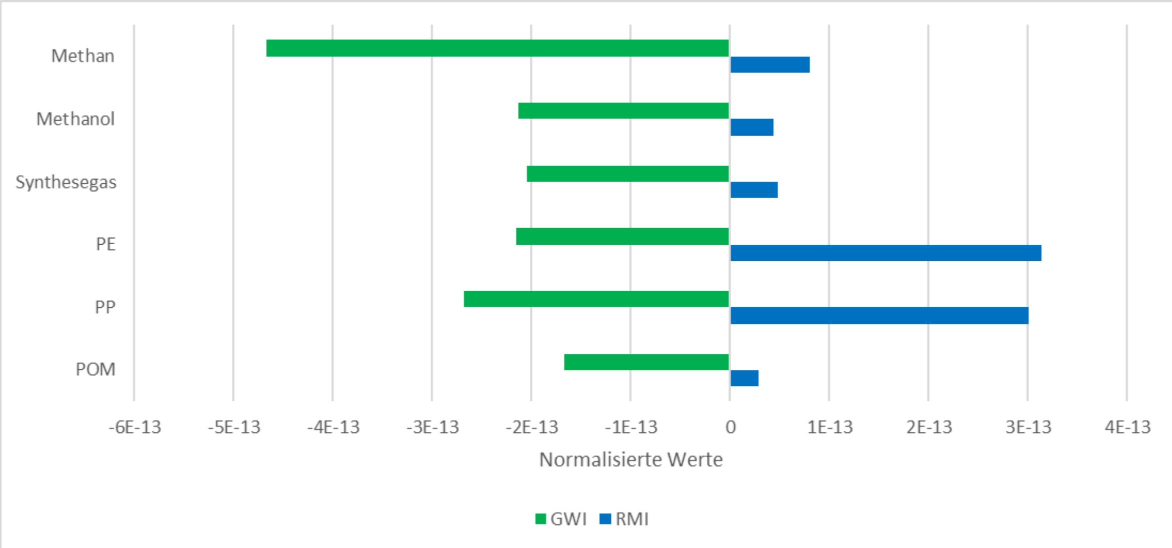


Figure 21: Normalised reductions (minus) and increases (plus) of environmental pressures through substitution of CO_2-based for fossil-based basic chemicals and polymers.

Cumulative energy demand

The **Cumulative Energy Demand (CED)** of a product represents the direct and indirect energy use, in MJ units, throughout its life-cycle, including the energy consumed during the extraction, manufacturing and disposal of the raw and auxiliary materials. Total CED is composed of fossil cumulative energy demand (i.e. from hard coal, lignite, peat, natural gas, and crude oil) and the CED of nuclear, biomass, water, wind, and solar energy in the life-cycle. See Huijbregts et al. (2010).

CED is complementary to GWI. When mainly fossil energy is used CED and GWI usually deliver similar results. However, when renewable energy is used CED may show different results. This is the case for the CO_2-based chemicals studied.

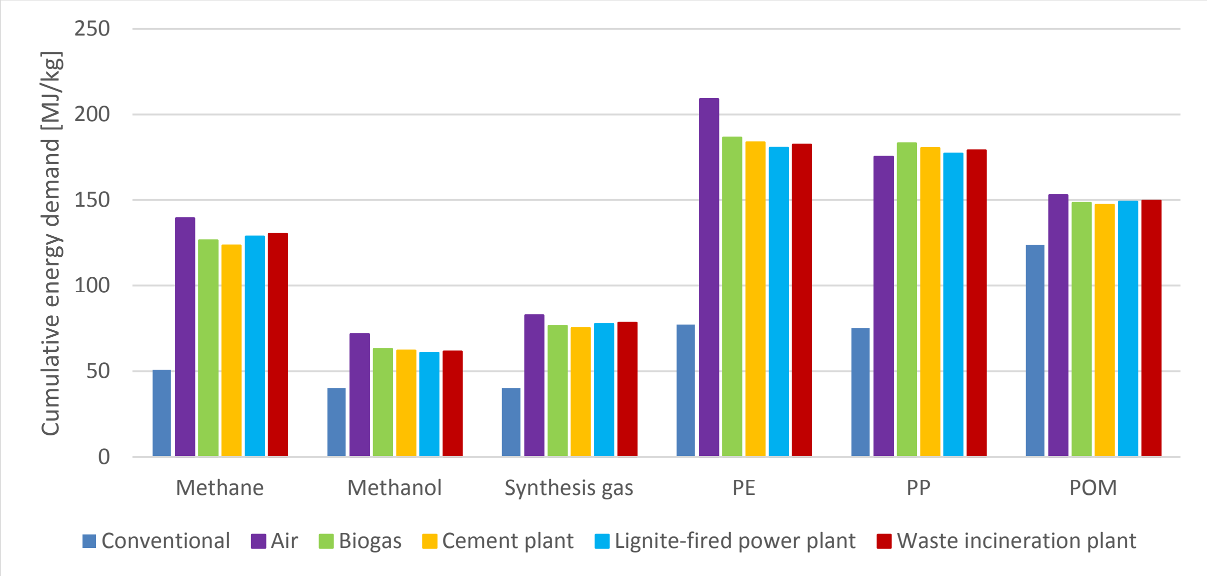


Figure 22: CED for production of basic chemicals and polymers from different CO_2 sources compared to conventional production

The conventional routes have significantly lower CEDs than the CO_2-based routes. The relative difference to the CCU equivalent is lowest for POM production. Overall, the CO_2-based POM process has the lowest relative increase in additional energy use compared to the other routes. Methanol has, on average, the second lowest relative energy demand compared to conventional.

Water input

The water input process gives an estimate of how much water a production process will consume based on the functional unit. According to DIN (2016) the water footprint has to take into account the availability or scarcity of water, which was not analysed in this study as that would have been beyond the scope hereof.

The electrolysis of water to produce hydrogen plays a significant role in CCU. According to the life-cycle inventory approximately **9 kg of water per kg H_2 are required**. The amount of hydrogen per kg of product is different for every product.

The water input for the analysed processes is depicted in Figure 23 without a separate plotting of the CO_2 sources, as according to the life-cycle analysis inventory in the appendix none of the evaluated **capturing processes from various sources** have a significant water consumption. The PE/PP water input could not be calculated, as the cooling water data for polymerisation of ethylene and propylene to PE/PP based on ecoinvent 3.1. is not consistent with conventional process data. The POM water input could not be calculated, as the data set from Plastics Europe (2011) does not enable one to specify the water input of the main processes. The following diagram compares the methanation, methanol synthesis and synthesis gas production processes based on the amount of water that is consumed for the production processes from cradle-to-gate, based on biogas as the CO_2 source. The description 'without turbine use' implies that water for hydropower generation is not included.

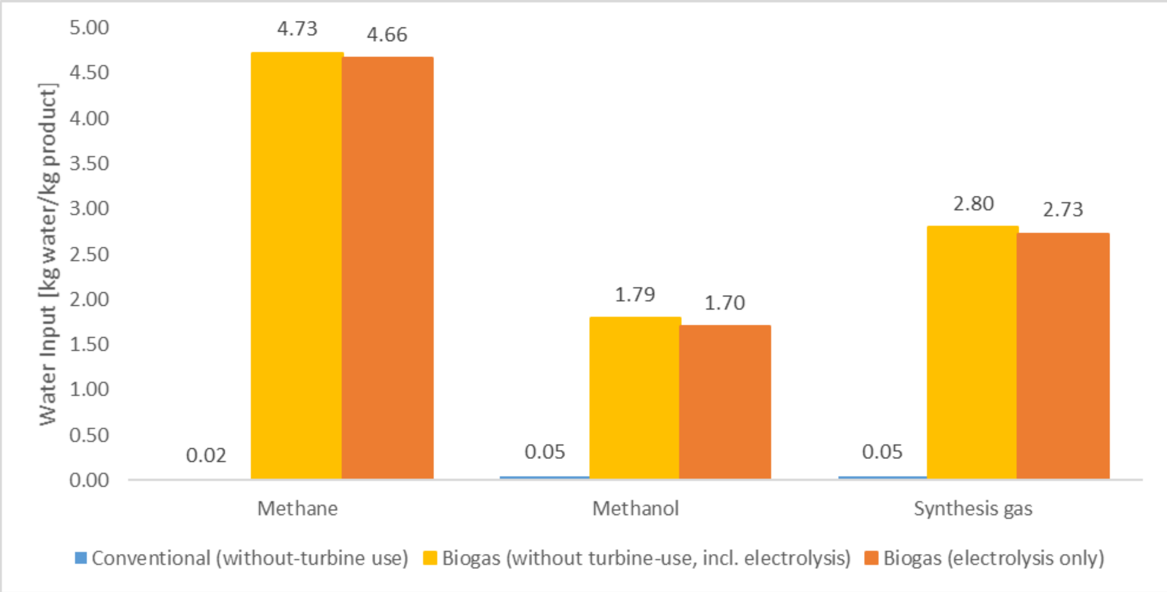


Figure 23: Water input for production of basic chemicals and polymers from carbon capture and utilisation process with biogas as CO_2 source. Water use for hydro-power generation is not included.

Methane has an overall higher water input for electrolysis compared to methanol or syngas, because the methanation reaction requires more hydrogen than the methanol synthesis. Methane requires 4.73 kg of water per kg, Methanol 1.79 kg of water per kg and synthesis gas 2.80 kg water per kg of product. The water input for electrolysis is actually consumed water that is chemically transformed in the process. The electrolysis causes an increased water demand, as water is used as a raw material, which is not the case in the conventional route.

Water consumption and withdrawal can become a problem if processes are located in areas where water is scarce. Utilisation of renewable energy from sunlight may be a reason to locate CCU processes in regions with water scarcity, which then may become an issue. Regionalised LCA is a suitable method to analyse the water footprint further, as it takes into account actual local water conditions.

Spatial scenarios for methane and methanol production

The scenarios contain two case studies which reflect the **spatial** relationship between wind power farms and industrial plants. A detailed explanation on how the scenarios are built and which factors are taken into account can be found in the methodology chapter in the Appendix (4.3.2: LCA Methodology). The following scenarios are considered to evaluate how product transport of methane and methanol affects GWI.

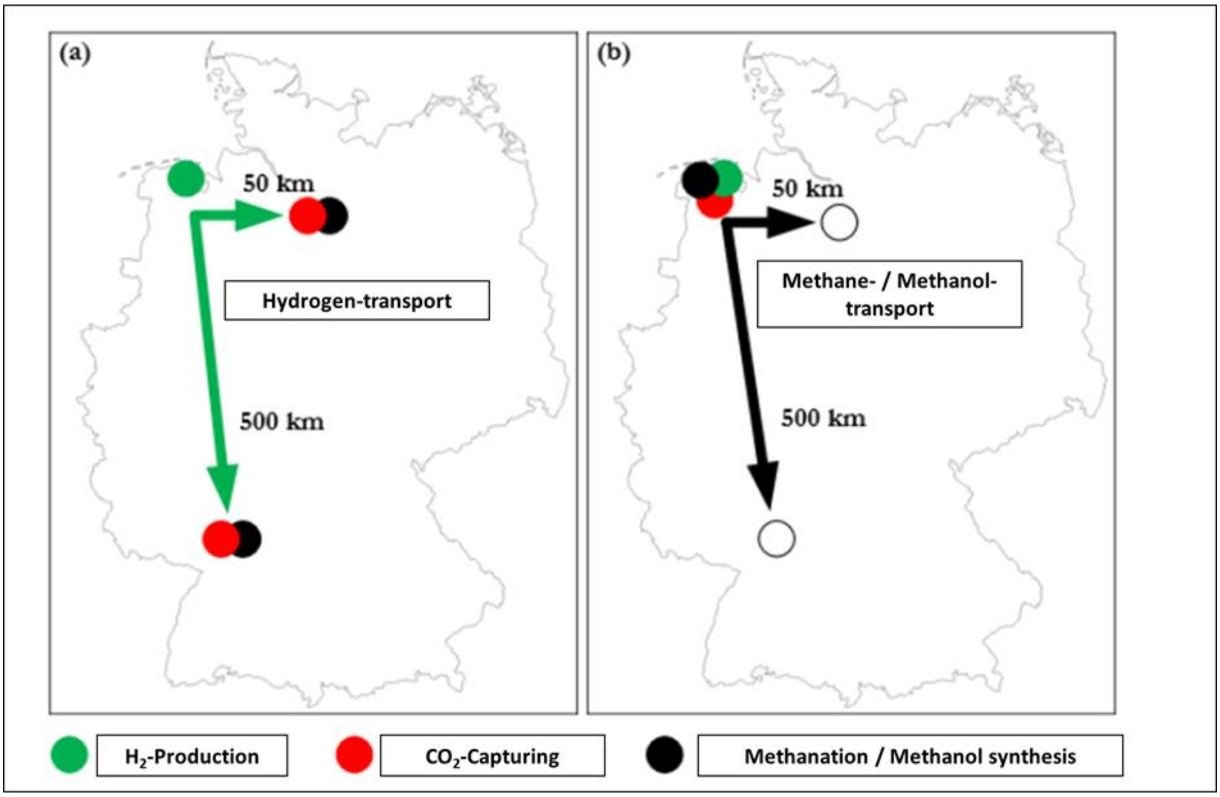


Figure 24: **Transporting of hydrogen (a) and CO_2-based methane / methanol (b) (based on Hoppe (2018); (not to scale) (Picture source (map of Germany): Dalet, 2016)**

(a) The transporting of hydrogen in a pipeline to the CO_2-source and chemical plant, where methane or methanol are produced and could be used for further processing or used as fuel.

(b) The local combined production of hydrogen, CO_2-capture and methane or methanol production and the transporting of methane or methanol to processing plants producing polymers or to fuel stations.

For each scenario transporting distances of 50 km and 500 km are considered.

- **Methane**

All cases have a negative climate impact. When the CO_2 source is at a distance of less than 50 km the transporting can involve either with hydrogen or methane, as the difference in greenhouse gas emissions is very low. At a transport distance of 500 km hydrogen transporting is more favourable in terms of GWI than the transporting of synthesised methane.

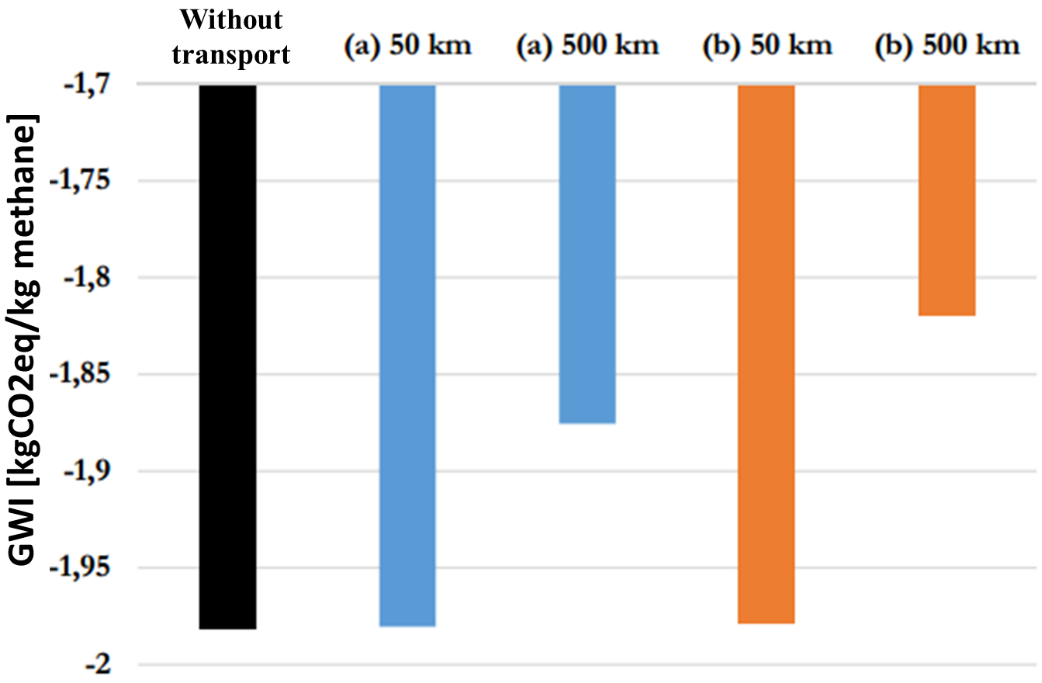


Figure 25: GWI for methane production considering (a) transporting of H_2 and (b) transporting of methane for 50 km and 500 km (Hoppe, 2018)

Growing transport distances correlate with higher RMI. RMI increases if methane instead of H_2 is transported in a pipeline. While the difference in transporting of both chemicals over a short distance (50km) is negligible, it becomes significant at a distance of 500 km.

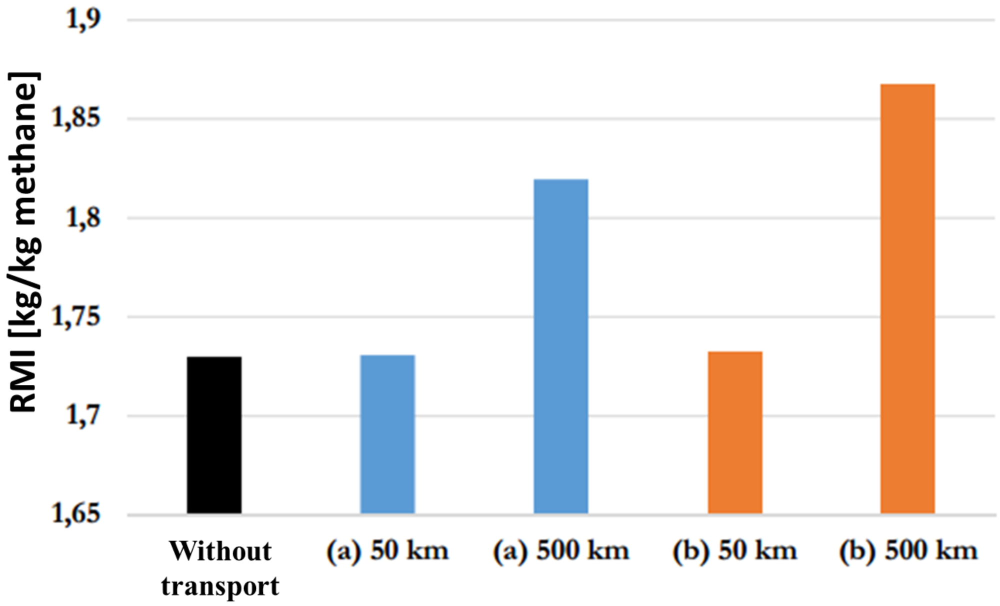


Figure 26: RMI for methane production considering (a) transporting of H2 and (b) transporting of methane for 50 km and 500 km (Hoppe, 2018)

- **Methanol**

Transporting methanol over distances up to 500 km by heavy goods vehicle (HGV) would not increase GWI higher than 0.1 kg CO_2eq per kg of methanol and thus would be of minor relevance. In the short distance scenario (up to 50 km) methanol vs hydrogen transport would not differ. Transporting of hydrogen by pipeline over 500 km would cause 0.05 CO_2eq per kg of methanol less GWI than transporting of methanol by HGV.

At the short distance (50 km) the transporting of methanol via HGV has only a marginally higher RMI. Longer distances have a higher impact on RMI.

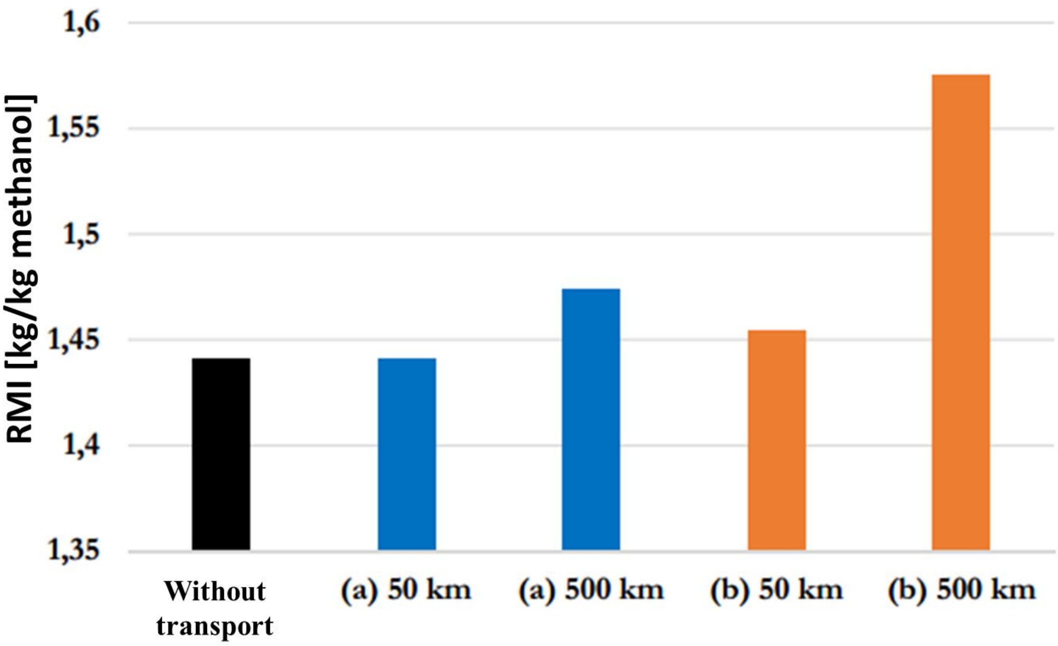


Figure 27: RMI for methanol production considering (a) transporting of H2 and (b) transporting of methanol for 50 km and 500 km (Hoppe, 2018)

The energy demand for the hydrogen or methane injection into a high-pressure grid (transport over long distances) would be connected to relatively higher environmental impacts due to the necessary compression. The energy demand for the injection into a low-pressure grid (transport over short distances) would not be of importance. The transporting of liquid methanol by HGV would not make compression necessary, so the environmental impacts would be a direct effect of the transport and increase proportionally with distance.

The climate impact of transporting hydrogen is in all cases lower than the climate impact of transporting methane or methanol. This can be explained by the lower transport volume of hydrogen in relation to the transport volume of the target product. Over long distances the transport per unit mass of gases such as hydrogen and methane in the pipeline would cause lower greenhouse gas emissions than the transporting of methanol by HGV.

Cross sectoral scenarios

Comparing inter sectoral scenarios helps to evaluate whether it makes sense given ecological aspects to use CO_2-based methane either as fuel for transportation or as material for the chemicals industry. **A first comparison** has been undertaken under the assumption to use natural gas or synthetic methane for car transport or for the steam re-forming process.

The results show that material use within the chemical industry may lead to slightly more favourable climate effects than use in transport. The differences in greenhouse gas emissions result from differences in energy required for pipeline transport; different pressure levels need to be passed from the production outlet to the point of further use, including differences of the pressure within the natural gas pipeline system (between high and lower pressure grid for long-distance vs regional distribution).

The replacement of natural gas leads to lower climate effects in both scenarios. If CO_2-based methane is used as fuel, the positive climate effects are enlarged if it is also transported in a high-pressure gas net. The contrary is the case if CO_2-based methane is used as a material for steam gas re-forming. In this case supply via a low-pressure gas network and thus a more close-by production would be more favourable.

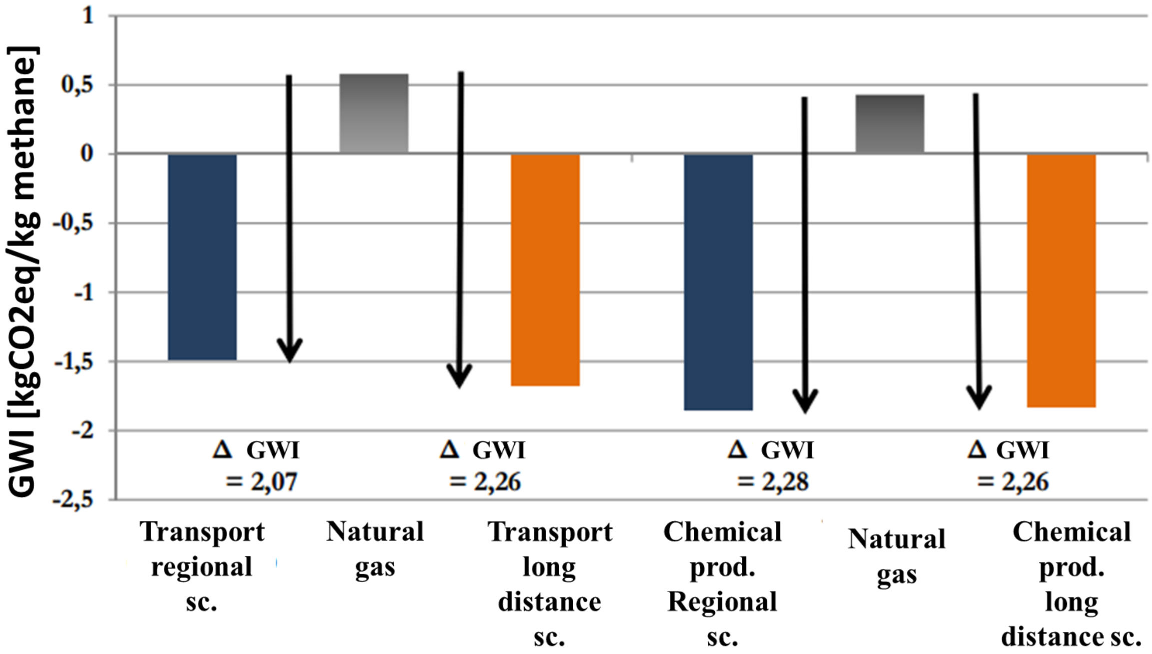


Figure 28: GWI reduction potentials for the replacement of natural-gas-based methane by CCU-methane (Hoppe, 2018)

Concerning the question of whether it is more advantageous to use CO2-based methane within the chemicals industry for steam re-forming or as a fuel, the potential to lower GHG emissions of both options must be compared. In the long-distance scenario the potentials for the material and energetic use are the same because natural gas and CO_2- and H_2-based methane are transported at under a pressure of 80 bar. The final pressure conversions are identical as well. Therefore differences exist only at the regional scenario.

In the case of regional supply the GHG saving potential would be higher if CO_2-based methane is used for chemical synthesis (2.28 instead of 2.07 kg of CO_2eq per kg of methane) because an additional amount of 0.21 kg of CO_2eq per kg of methane could be saved.

Energy scenarios

Energy scenarios based on different sources for electrical energy have been compared to identify electricity requirements for CCU processes. An explanation on the methodology can be found in the methodology chapter of the Appendix (4.3.2: LCA methodology).

In the first scenario we assumed that CCU production of methane and methanol were based solely on renewable energy from wind power. In the second scenario we assumed that the German grid mix was used. The production is compared to the conventional production of the chemicals.

Wind power represents renewable energy generation which may be assumed to grow in the future. The German grid mix represents the current conventional energy mix. This mix would have to be used for CCU if no surplus power or other renewable energy is available.

If energy from the public grid at a time of a high load factor serves as an energy source, GHG emissions would rise by 14.8 kg of CO_2-eq per kg of methane and 5.2 kg of CO_2-eq per kg of methanol.

The results show that GHG emissions will be extremely high if energy from the public grid is used. This results from the energy mix for Germany: about one third thereof comes from coal.

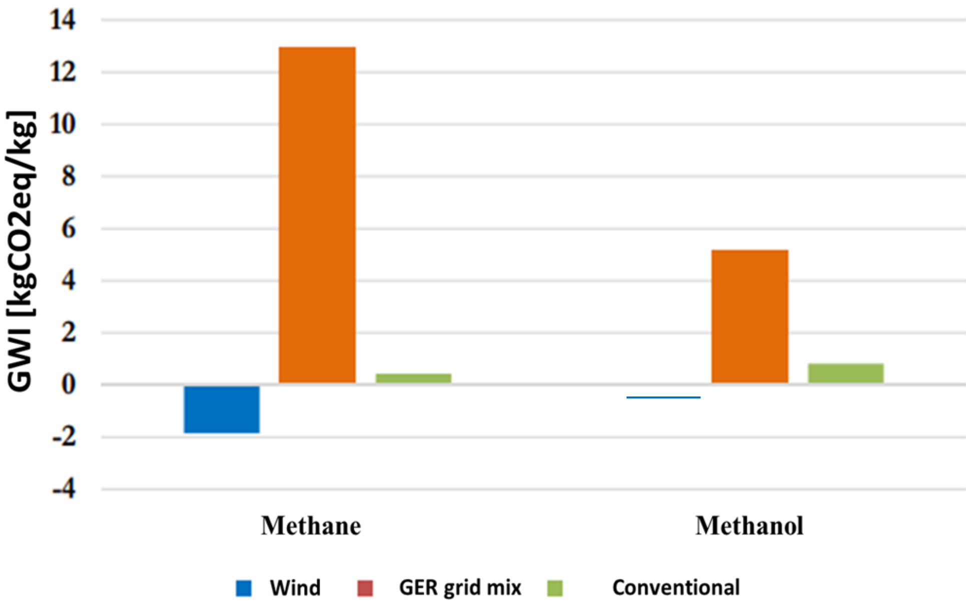


Figure 29: GWI for different energy sources for the electrolyser (Hoppe, 2018)

According to the table below the high amount of offered energy could be caused by high supply rates from wind energy (17.6% instead of 10.62%). Compared to energy carriers such as natural gas, coal and oil, it is cheaper to use lignite as an energy source. The share of this energy carrier is therefore hardly reduced and still contributes 30% of electrical energy generation. This leads to significantly higher climate effects and material intensities of CO_2-based chemicals compared to the base-scenarios, where exclusively wind energy is used. If the public energy grid is to serve as the energy source for CO_2-based methane production with decreased GHG load in comparison to the conventional production, the share of wind energy in the grid mix should be approximately 86% (Hoppe, 2018).

The requirement for a significant share of renewables in the grid mix is applicable for all EU countries or regions that intend to run the evaluated CCU processes with grid mix electricity.

The composition of the German grid mix can be found in chapter 4.3.3 of the Appendix (Data Basis for the LCA).

Using power from the public grid instead of wind energy would also significantly increase the raw material input in the event of a high load factor of the energy grid. The RMI of methane would increase to 12.2kg per kg and the RMI of methanol to 4.3 kg per kg. The relationships of the results involving TMR are the same than the ones for RMI.

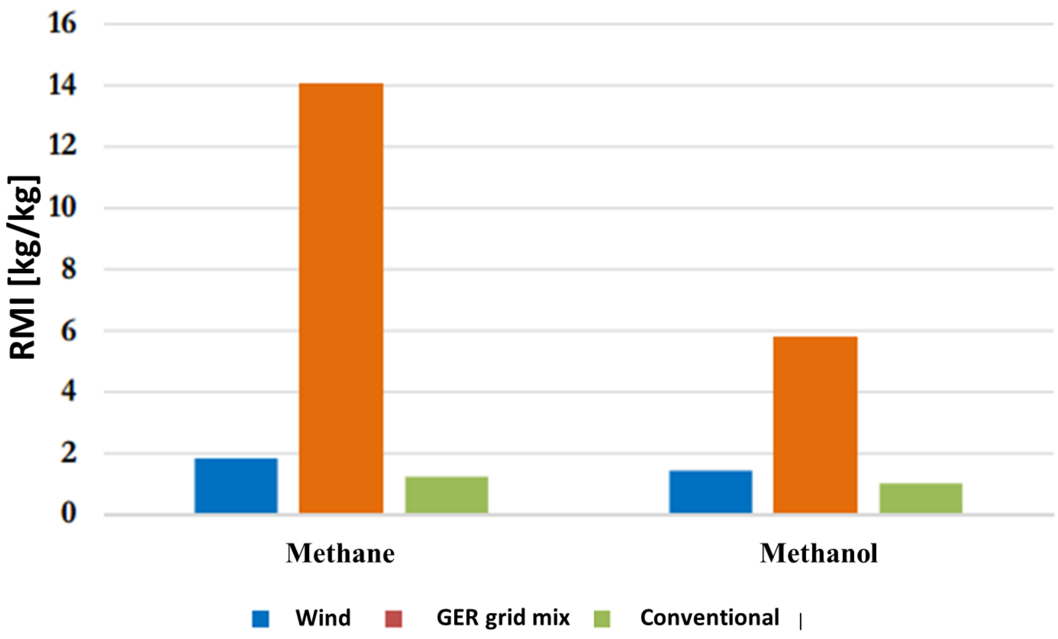


Figure 30: RMI for different energy sources for the electrolyser Source (Hoppe, 2018)

Discussion of LCA results

Negative values of GWI for CO_2-based methane production are due to the input of CO_2: 2.75 kg of CO_2 are used for the CO_2-based production of 1 kg of methane and 1.37 kg of CO_2 for the production of 1 kg of methanol. The final emission of the CO_2 in the end-of-life phase was not considered, as in the cradle-to-gate LCA approach both routes have an identical amount of final CO_2 emission. **The final CO_2 emission does not affect the GWI benefit from the production**. In our analysis modelled methane production via CO_2 from cement plants was the alternative with the lowest GWI, because heat recovery from methanation and heat recovery from the cement plant are assumed to satisfy the heat demand for CO_2-capturing in a way that only a low amount of external electricity is needed. In the case of methanol production via CO_2 from waste incineration shows the lowest GWI, due to a relatively low electricity demand (0.69 kg of CO_2eq/kWh) and no need for an external heat supply. Higher GHG emissions result from external heat supply from natural gas (0.26kg of CO_2eq/kWh) for capturing CO_2 from a biogas and cement plant and by work loss of lignite-fired power plants (1.2kg of CO_2eq/kWh). DAC is the most GHG emitting and material intensive CO_2-capturing option for methane and methanol production, due to the high heat and electricity demand.

Impacts on GHG emissions of methane and methane-based polymer production are relatively low, if the demand of electrical energy for capturing CO_2 is low. The demand for heat for capturing CO_2 can be neglected when recovering heat from methanation. CO_2-based routes for methanol production are most favourable if the thermal energy demand for capturing CO_2 is low or accessible burden-free, as methanol synthesis is less exothermal than methanation.

CO_2 capture plays a minor role in CO_2-based production in terms of GWI (Figure 31). For methane production **electrolysis dominates the GWI**, whereas in the case of methanol the electricity requirement for synthesis is the most important driver. The input of CO_2 leads to a negative GWI in both cases, which is significant for methane and rather balanced for methanol. In the case of methane the input of CO_2 dominates the GWI. The GWI of methanol is almost zero, due to an equal benefit for CO_2-input and expenses for CO_2 capture, H_2-production, and methanation.

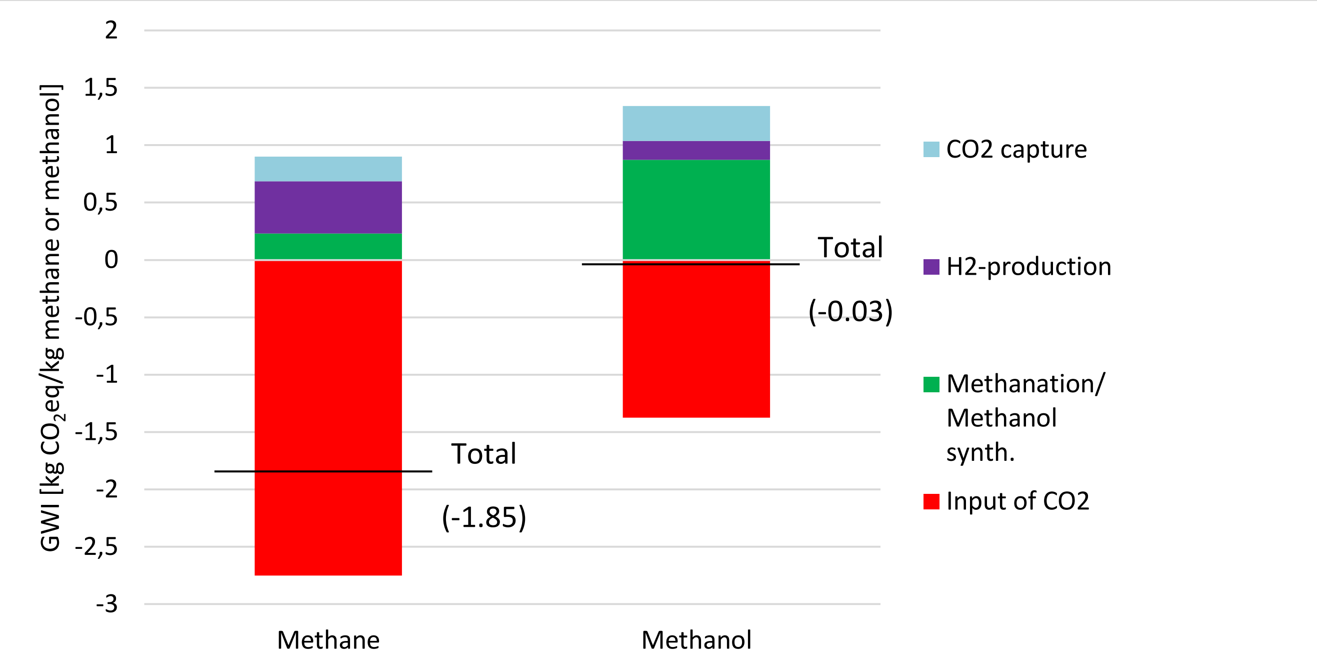


Figure 31: Processes determining GWI balance in methane and methanol production (assumed CO_2 source: biogas) (Hoppe, 2018)

The results of CO_2-based routes for synthesis gas, PE, PP, and POM depend on the impacts of the underlying basic chemicals. As the input of methane for the production of 1 kg POM (0.35 kg of methane per kg of POM) is lower than the input of methanol for PE and PP (around 2.6 kg of methanol per kg of PE or PP), higher savings of GHG emissions result for CO_2-based polyolefins.

Considering the material intensity of the different production routes, the CO_2-based alternatives exhibit a greater material intensity compared to the conventional paths. CO_2 from cement plants shows the lowest material intensity. This is due to the lower electricity required for capturing CO_2 from flue gases of a cement plant compared to other CO_2-sources. Another reason for the relatively low material intensity is the lower net heat demand, due to heat recovery from the cement plant and from methanation/methanol synthesis. The higher material demand of CO_2-based routes results mainly from the energy intensity of the electrolysis. In the case of methanation (assumed CO_2-source: biogas), 80% of RMI and 65% of TMR result from the construction and maintenance of the wind energy plant. The TMR and RMI for methanol production are below these values due to the lower stoichiometric input of hydrogen and therefore lower demand for wind energy. The RMI (which consists mostly of abiotic primary materials) and the TMR for wind power were calculated as 0.05 kg/kWh and 0.10 kg/kWh, respectively. These values were derived for a single wind turbine (0.8 MW peak power) with an operating life of 20 years and 1,680 wind-load hours per year. Wind farms with 5 MW turbines produce electricity offshore with a TMR of 0.18 kg/kWh (Wiesen et al., 2010) and 0.09 kg/kWh onshore (Wiesen 2013). Therefore the figures provided here represent nearly the same range of primary material requirements of wind power. The TMR and RMI of fossil energy sources, such as coal-based electricity, would be significantly higher.

As explained above, a trade-off between GWI and material resource requirements has to be taken into account to assess the environmental burden of CCU. Normalisation represents one way of comparing different environmental pressures. The results presented may be interpreted in a way that the CO_2-based production of methane, methanol, synthesis gas, and POM would be reasonable as the savings of GWI – in relation to the absolute pressures at the economy-wide level – would be higher than the additional material resource requirements. This result is mainly caused by the input of CO_2. In contrast, the production of CO_2-based polyolefins via MTO would not be reasonable if one could not accept that the reduced GHG emissions go along with disproportionately higher resource requirements. This is caused by the energy-intensive MTO-process, which also causes a relatively high GWI. Although we calculated an input of 3.59 kg of CO_2 per kg of PE, the difference of GWI between conventional and CO_2-based production is on average only 0.58 kg of CO_2eq per kg of PE. In contrast, the increase of RMI is in average 4.9 kg per kg of PE.

Cumulative energy demand was in a normal range, with POM having the lowest additional, relative energy demand. Overall, CCU routes show a higher energy demand than conventional routes, with POM having the lowest relative increase.

Water accounting shows the consumption of water with regard to the electrolyser as a potential main water consumer and should be considered if water availability from environmental systems is limited.

Hoppe et al. (2017) carried out a sensitivity analysis for the example of methane production from CO_2 in raw biogas indicating that the use of electricity from renewable sources such as wind power for electrolysis is a necessary condition for reducing GWI, RMI, and TMR. Using electricity from the grid instead of wind, GWI would increase to 17.2kg of CO_2eq per kg of methane. Furthermore, RMI and TMR would grow by about 914 and 1,561%, respectively, (indicating that power supply by conventional plants is significantly more material intensive than energy from wind turbines). If wind power were used for all main processes as an electricity source, in particular for capturing of CO_2 and methanation, the GWI of the entire process chain would decrease further by around 23%. RMI would decrease by 18% and TMR by 33% in this case (not yet considering lower primary material requirements reduced by higher recycled input, in particular for the metals).

If the energy requirement of waste incineration plants for CO_2-capture were equivalent to that of lignite-fired power plants (0.164 kWh per kg of CO_2, as described in Chapter 4.4.3, Data Basis for the LCA), GWI would decrease by 8% and the material intensity would decrease by 5% to 9%. Heat recovery from the cement plant for CO_2-capture (0.18 kWh per kg of CO_2) is advantageous for methane production. If natural gas were used as a heat source instead of heat recovery from the cement kiln, GWI would increase by around 0.10 kg of CO_2eq per kg of methane, and RMI and TMR would go up by 0.04 and 0.06 kg per kg of methane, respectively. The increases for methanol production would be in a similar range. While GWI would rise by about 0.09 kg of CO_2eq, RMI and TMR would increase by about 0.04 and 0.05 kg per kg of methanol, respectively.

If waste heat from external sources could be used – in the chemicals industry exothermal reactions often require cooling – and replace natural gas for CO_2-capture from the air, GWI would be lowered by around 0.5 kg of CO_2eq or 45%. The effects on TMR and RMI would be negligible (–5% to –10%), due to the low material intensity of natural gas. This means that the GHG emissions of DAC would be comparable to or lower than that of point sources as long as burden-free thermal energy was accessible. There are no effects of using burden-free thermal energy for methane production from CO_2 point sources (biogas and cement), as heat recovery from a co-located methanation plant would already be sufficient. Using heat burden-free for methanol synthesis from biogas, GWI would decrease by about 0.19 kg of CO_2eq per kg of methanol.

Due to the fact that simulation data was used where plants do not (yet) exist, the significance of the results is limited. For methane production Hoppe et al. (2017) compared GWI results with an existing methanation plant. In practice, methanation technologies exhibit 17% to 28% lower GHG savings compared to the simulation.

As CCU is a new field of research only a few studies about the environmental performance of CO_2-based basic chemicals and polymers have been published. Sternberg and Bardow (2015) considered a lignite-fired power plant as a CO_2-source. Concerning the CO_2-based production of methane, methanol and synthesis gas, they calculated a lower GWI compared to the conventional production alternatives. This corresponds with our findings. A study by von der Assen & Bardow (2014) investigated the impacts of production and utilisation of polyoxymethylene units for polyurethane production. They also assessed environmental benefits of CO_2-based polymers compared to conventionally produced polymers. A more detailed comparison is hardly possible, due to individual results for POM not being mentioned.

Further processes reported in literature

LCA on polyols for polyurethane production

The production of polyethercarbonate polyols by copolymerisation of CO_2 and epoxides has been analysed by von der Assen & Bardow (2014) using a cradle-to-gate LCA.

The reaction for the polymerisation of propylene oxide (PO) and carbon dioxide to polyehtercarbonate polyols using a double metal catalyst (DMC) and a multifunctional alcohol as a starter is shown in the following figure.

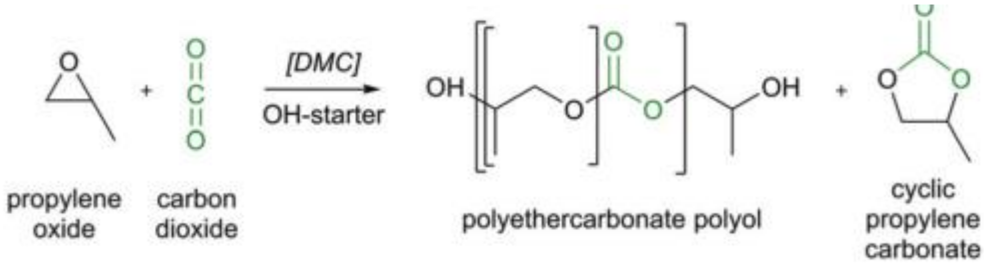


Figure 32: Polymerisation of propylene oxide (PO) and carbon dioxide (CO_2) to polyethercarbonate polyols using a DMC catalyst and a multi-functional alcohol (e.g. glycerol) as starter (von der Assen & Bardow, 2014)

CO_2 partially replaces energy- and emission-intensive epoxides. Still, energy requirements and GHG emissions are caused by the provision of epoxides required as co-reactants as well as by the provision of CO_2 itself

The analysed product system comprises production and purification of CO_2-based polyethercarbonate polyols as well as all processes for the provision of energy and feedstock. In particular, the provision of the feedstock CO_2 is included: CO_2 has been captured from a lignite power plant, compressed and transported to the polyol production plant (the actual production uses a CO_2 source from Covestro's own chemicals facility). The major considered environmental impacts are global warming (CO_2-equivalents) and fossil resource depletion (oil-equivalents). Regarding these impacts, the product system for CO_2-based polyethercarbonate polyols is compared to an equivalent product system consisting of conventional polyols production and a lignite power plant without CO_2 capture.

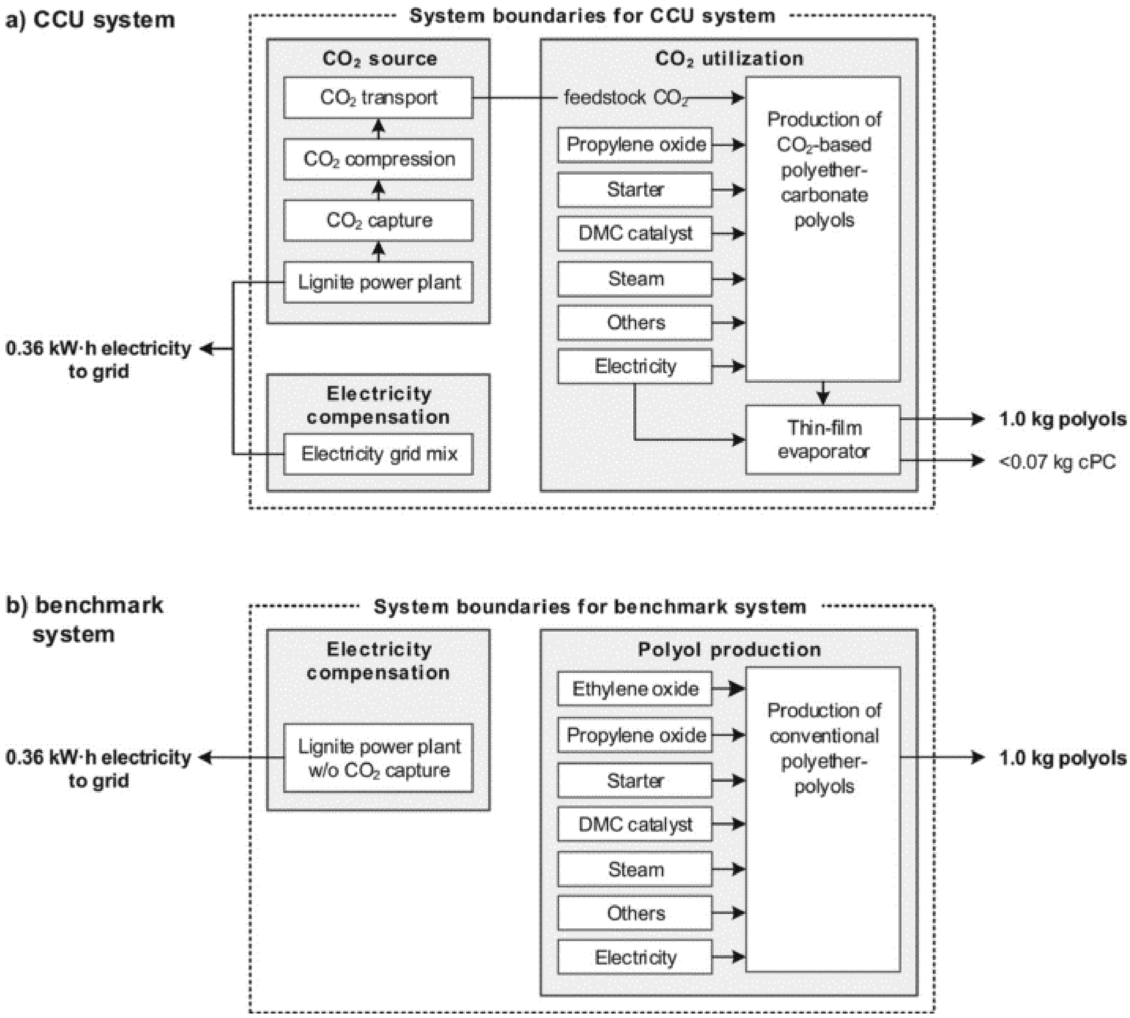


Figure 33: (a) Product system for CO_2-based polyethercarbonate and (b) product system for conventional polyether polyols from fossil-based feedstocks (von der Assen & Bardow, 2014)

Figure 33 described the systems for the LCA as follows:
(a) Product system for CO_2-based polyethercarbonate polyols: CO_2 utilisation (right box) consists of production of polyethercarbonate polyols and separation of the by-product cyclic propylene carbonate (cPC) as well as provision of all feedstocks and energy. Feedstock CO_2 is provided by a lignite power plant with CO_2 capture (CO_2 source, top left box). Additional electricity from the grid mix compensates for the energy penalty for CO_2 capture (electricity compensation, bottom left box).
(b) Product system for conventional polyether polyols from fossil-based feed-stocks: Polyol production (right box) consists of the production process itself as well as the provision of all feedstocks and energy. Electricity generation (left box) from a lignite power plant without CO_2 capture is added to the product system to enable a sound comparison to the CCU system (a) with identical product outputs (functional unit). (von der Assen & Bardow, 2014)

The cradle-to-gate impacts on global warming and fossil resource depletion are assessed for the functional unit of 1.0 kg of polyols and 0.36 kWh of grid electricity. The latter relates to the amount of CO_2 that is captured to produce one kg of polyol.

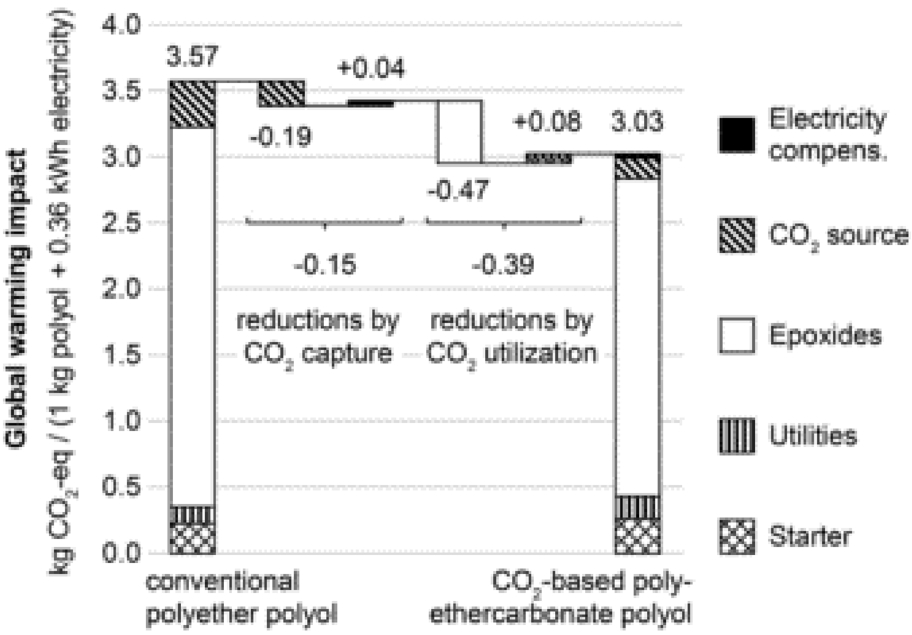


Figure 34: GWI for product system of conventional polyether polyols (left) and CO_2-based polyethercarbonate polyols (right) (von der Assen & Bardow, 2014)

Figure 34 shows the global warming impact for the benchmark system with conventional polyether polyols, and for the CCU system with polyethercarbonate polyols containing 20 wt% CO_2. In both systems the largest contributor to total GHG emissions is the production of epoxides (81% and 80%). By utilising CO_2 as feed-stock for polyols the system-wide *GHG emissions can be reduced by 15%* (−0.54 kg of CO_2eq per functional unit). About 28% of the total GHG emission reductions originate from CO_2 capture effects (−0.15 kg of CO_2eq per functional unit) as a result of emission reductions at the CO_2 source and additional emissions for electricity compensation. Major GHG emission reductions of about 72% originate from CO_2 utilisation in polyol production (−0.39 kg of CO_2eq per functional unit) which can be explained by the replacement of emission-intensive epoxides with CO_2.

CCU literature clearly distinguishes the amount of CO_2 used from the avoided CO_2eq emissions. The following figure illustrates the amount of avoided CO_2eq emissions per amount of CO_2 incorporated into polyethercarbonate polyols for CO_2 contents of 10, 20 and 30 wt%.

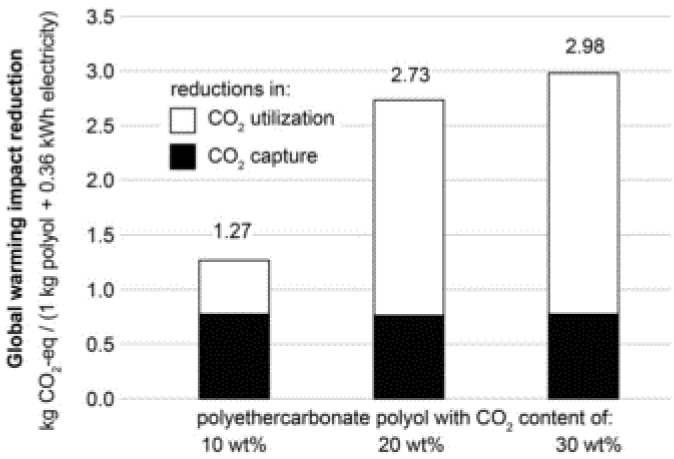


Figure 35: Global warming impact reductions in kg of CO_2 equivalents per kg of feedstock CO_2 incorporated into polyols (von der Assen & Bardow, 2014)

For all CO_2 contents the amount of avoided CO_2eq emissions is greater than the amount of CO_2 incorporated into polyols. The main reason for this effect is the much larger global warming impact of PO (1.74–4.5 kg of CO_2eq per kg) and EO (1.6 kg of CO_2eq per kg) compared to CO_2 incorporated (below 0.2 kg of CO_2eq per kg). For 10 wt% CO_2 content mainly EO is replaced. For higher CO_2 contents the additional CO_2 incorporated replaces PO, making possible larger reductions than EO substitution, although in a non-linear manner.

The LCA shows that the utilisation of CO_2 makes possible relevant impact reductions: compared to conventional polyether polyols **polyethercarbonate polyols with 20 wt% CO_2 reduce GHG emissions (by 11%–19%) and save fossil resources (by 13%–16%).**

We used the following values from Figure 37 for the EU-GWI reduction calculation in chapter 4.4.4: GWI reduction for 30 wt% CO_2 content: 2.98 kg of CO_2eq per kg of product; GWI reduction for 10 wt% CO_2 content: 1.27 kg of CO_2eq per kg of product

<u>*LCA for synthetic fuels via the Sunfire process*</u>

The Sunfire process was excluded from our own analysis due the unknown composition of the produced chemical fuel. It can be assumed that the product has a high degree of similarity to conventional diesel. We refer to an LCA for the Sunfire process indicating the results per energy unit produced and not in kg per product. In the case of CCU fuel technology the values represent a reasonable comparative indicator, but the results are **not directly comparable to the results of the LCA calculations shown above**.

An LCA for the Sunfire process has been carried out by the University of Stuttgart (2015) and focuses on the production of synthetic fuels from the Sunfire high temperature electrolysis and Fischer-Tropsch synthesis. The synthetic diesel can be used as an energy carrier to replace fossil-based energy carriers, such as conventional diesel. The production is based on CO_2, water and renewable energy.

The Sunfire company started to run the ‘fuel 1’ power-to-liquid plant in November 2014. The plant has a capacity of 159 l of synthetic diesel per day. Functionality is proven.

The methodology has been described by Universität Stuttgart (2015). A well-to-wheel approach is conducted. The manufacturing of the fuel and use in a vehicle are considered. The following scheme shows the boundary of the system for the LCA:

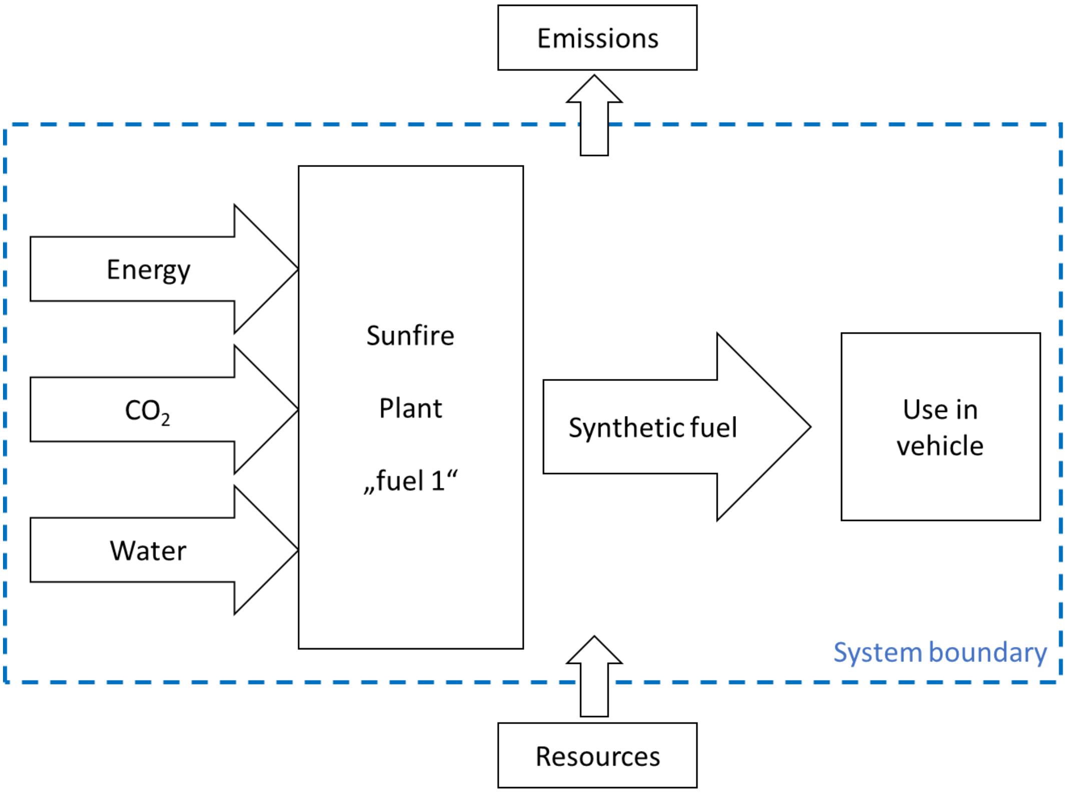


Figure 36: System boundary for the considered wheel-to-wheel approach by Universität Stuttgart (2015)

Assumptions and basic conditions:

- CO_2 is captured from air via direct air capture (DAC). The air-capture technology is based on Climeworks AG (2015) and requires thermal and electrical energy.
- Thermal energy is currently provided partly from waste heat. The production is modelled for two scenarios. The first is thermal energy generation from natural gas and the second is thermal energy completely from waste heat, which is accounted to have no environmental impacts. The performance of the '**fuel 1**' plant is estimated in-between the scenarios.
- Electrical energy consumption is calculated based on the German grid-mix and different renewable energy technologies.

The parameters considered for the LCA for the combination of the 'fuel 1' and direct air capture can be found in the Appendix, in Section 4.4.5:

Table 10: Parameters for the combination of 'fuel 1' and DAC as stated by Universität Stuttgart (2015)

	Parameter	Fuel 1 & DAC natural gas	Fuel 1 & DAC waste heat
Fuel 1 – Buildings and reactors	Construction and dismantling of the building and the refinery components	Considered	
	Maintenance of the refinery components	Not considered	
Operation of fuel 1	Specific gas torch power [kW]	0.75	
	Operating hours [h/a]	8,000	
	Plant life-time [a]	20	
	Efficiency of fuel 1 [%]	65	
	Electricity supply	German grid mix, GE hydropower, GE photovoltaics, GE **wind power**	
CO_2-Source	CO_2 from atmosphere via DAC		
Operation DAC	Electricity supply	Same source as for fuel 1	
	Thermal energy supply	Natural gas	Waste heat
Output	Fuel [MJ]	1	

In the study an energy supply from a lignite-fired power plant was evaluated and found to have no environmental benefit. Therefore lignite-fired power plants are considered only as potential CO_2 sources.

The main results are presented in the study are depicted in Figure 37.

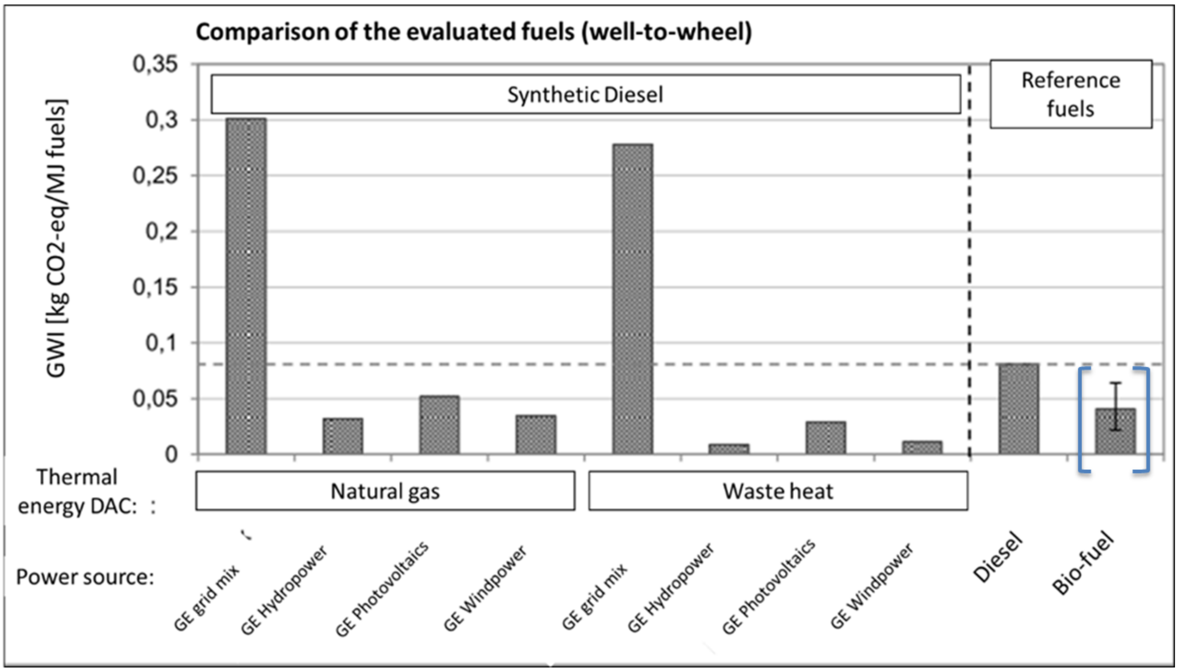


Figure 37: Results of the comparison of fuel 1 and CO_2 from air capture (well-to-wheel) based on Universität Stuttgart (2015); GE=German; [] Biofuels data does not consider iLUC adequately

The figure shows the results for the operation of the DAC with natural gas in one case, and with waste heat as the energy source in the other case. The results are shown in combination with different power sources for the operation of the plant. Diesel and biofuel production are presented as conventional production routes. The GWI data on biofuels should be treated with caution because full attribution of indirect land use change to first generation of biofuels would lead to a higher GWI than conventional fuels (UNEP, 2009, 2014).

Using the German electricity grid mix for CO_2-based fuels results in much higher emissions compared to the conventional route. If 'fuel 1' is produced with renewable **electricity**, a GWI reduction of 35% to 85% can be achieved.

The thermal energy consumption of the DAC is another relevant parameter. Production with 100% waste heat shows the biggest impact reduction.

Altogether, synthetic diesel production with the Sunfire PtL process has the potential to save GHG emissions compared to fossil-based diesel. The key parameter is the power source used for the plant operation. Synthetic diesel shows advantages over fossil diesel if renewable electricity is used.

We used the following values from Figure 37 for the EU GWi reduction calculation in chapter 4.4.4: GWI reduction for waste heat and GE wind-power: 0.7 kg of CO_2eq / MJ Fuels; GWI reduction for natural gas and GE wind-power: 0.45 kg CO_2eq / MJ Fuels.

LCA for CO_2 sequestration in magnesium silicate rock

The availability of valid LCA on mineralisation processes is limited. One example is discussed in this Section, while technical aspects relevant for environmental performance are reviewed in the subsequent Section.

Nduagu et al. (2011) performed an LCA addressing the energy and environmental implications of sequestrating CO_2 from a coal power plant using magnesium silicate rock. The LCA is based on simulation results and assumes serpentine mining based on data for Olivine. The mineral olivine is harder than serpentine, hence this a conservative estimate, as it can be assumed that the serpentine process requires less energy for mining and grinding. Energy consumption is based on a coal power plant in Canada.

Nduagu et al. compared options to produce magnesium carbonate; however, they did not compare it to conventional products which could replace magnesium carbonate, although it could be sold. The results are stated in GWP reduction in kg per kg of mineralised CO_2. A comparison of the process to a conventional production is not included. The aim of the LCA is to prove that an improved mineralisation process could store more CO_2. The value generation would be low and no pilot plant is available.

An accounting type life-cycle assessment (LCA) of the mineralisation method under development at Åbo Akademi University (ÅAU), Finland, has been presented and the results compared with the process developed at the National Energy Technology Laboratory (NETL), formerly Albany Research Council (ARC), in the US. The ÅAU process is a multi-staged route where CO_2 is sequestered via a process that first produces magnesium hydroxide, $Mg(OH)_2$, from magnesium silicate. The $Mg(OH)_2$ produced is later reacted with CO_2 in a high temperature gas/solid pressurised fluidised bed (FB) reactor, forming pure, stable and environmentally benign $MgCO_3$ as product.

Nduagu et al. (2011) address the following issues:

- the material and energy requirements for sequestering 1 tonne of CO_2 (t-CO_2) in mineral silicate;
- the overall greenhouse gas emission, in kg of CO_2eq per kg of CO_2, for sequestration associated with CO_2 mineralisation using serpentinite mineral;
- the priorities and opportunities for reduction of energy requirements and environmental impacts associated with mineralising CO_2;
- comparison of LCA results of the ÅAU mineralisation process route with those of the mineralisation process developed by NETL.

The following figures depict the analysed system and the system boundary from mining to production of magnesium carbonate (cradle-to-gate).

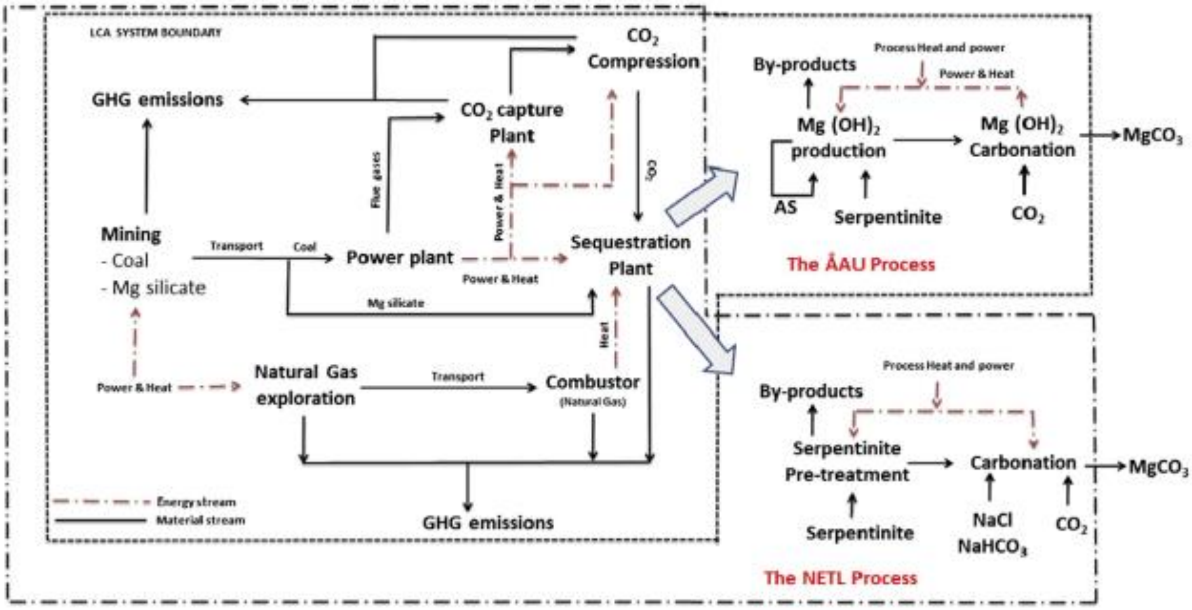


Figure 38: Schematic representation of the system boundary. The CO_2 mineralisation plant is expanded to show the ÅAU and NETL processes. AS represents the ammonium sulfate salt reagent used and recycled in the ÅAU process. (Nduagu et al., 2011)

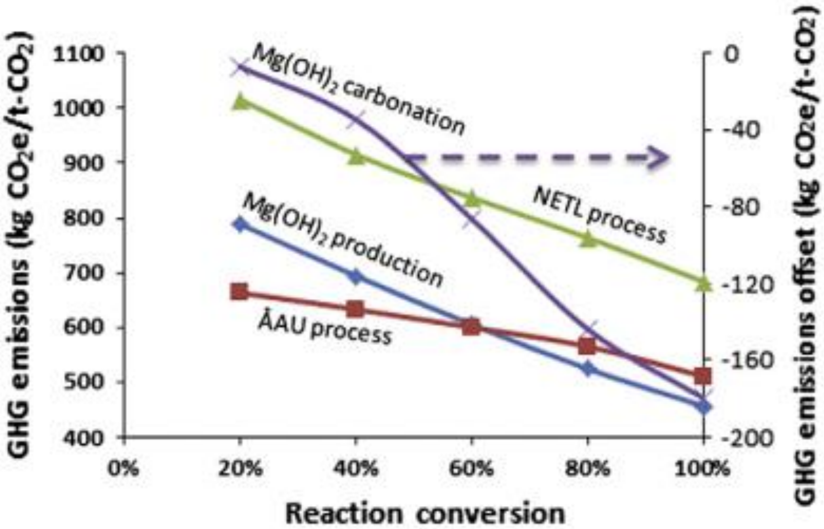


Figure 39: Effect of varying extent of reaction conversion of the two processes. GHG emissions caused per tonne of sequestered CO_2 are shown on the primary y-axis on the left side. The green and red plots are related to the left axis. GHG offset values associated with Mg(OH)$_2$ carbonation, depicted in purple and blue, are read from the secondary y-axis right. (Nduagu et al., 2011)

The GHG emissions are plotted based on the reaction conversion in the respective processes. The ÅAU process is compared to the NETL process. The purple and blue lines show the GHG offset based on secondary y-axis on the right side based on the reaction conversion. The ÅAU process has a higher reduction potential than the NETL process, as less GHG is produced per tonne of CO_2 sequestered. The GHG indicator decreases with an increase in reaction conversion.

In particular, the $Mg(OH)_2$ carbonation, which is relevant for both processes, requires a high reaction conversion to achieve maximum GHG savings (right secondary axis).

The energy requirements for processes such as CO_2 compression and CO_2 capture vary within the same range for both the ÅAU and the NETL processes (Figure 40). However, the GHG emissions of the former are significantly lower. Use of waste heat and process integration has been improved.

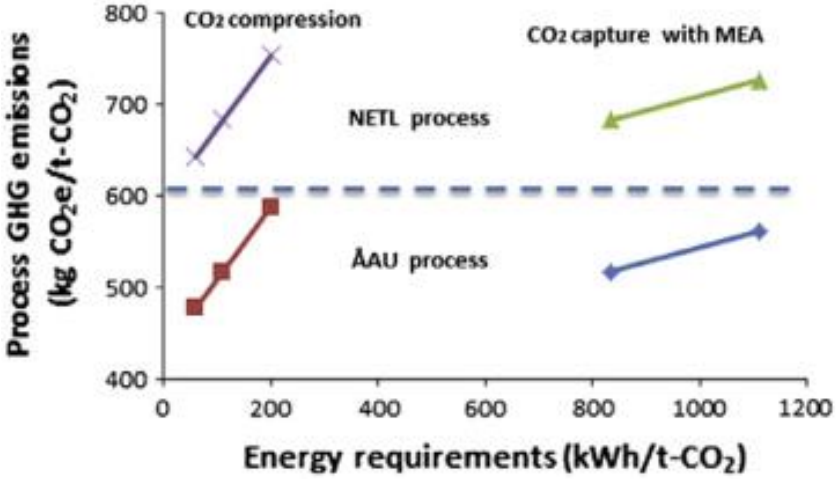


Figure 40: Effect of variability of energy requirements of CO_2 capture with MEA and CO_2 compression on the GWP of ÅAU and NETL processes (Nduagu et al., 2011)

Exergy calculations show that, with full heat recovery, mineralising 1 tonne of CO_2 using the ÅAU process requires 3.6 GJ per tonne of CO_2, while the NETL process needs 3.4 GJ per tonne of CO_2. Applying exergy analysis results of the ÅAU process (using allocation by mass of products) in the LCI model results in GWP of 517 kg of CO_2eq for every tonne of CO_2 mineralised. This means that 483 kg of CO_2 can be avoided when 1 tonne of CO_2 from a coal power plant is mineralised. On the other hand, the NETL process has an associated GWP of 683 kg of CO_2eq, meaning that 317 kg of CO_2eq are avoided via the NETL process route per tonne of CO_2 sequestered. The LCA results show that the ÅAU process has almost the same energy intensity but a lower GWI than the NETL process. Factors in the ÅAU process contributing to the lower environment impact include recoverability of the chemical reagent, lower thermal treatment temperature (at 400 °C, which may also makes it possible to use almost emission-free energy sources, such as solar thermal energy), the CO_2 reduction potential of the Fe and Ca by-products in sinter plants of the iron and steelmaking industries, and the heat recovery and/or power generation potential of the exothermic gas/solid $Mg(OH)_2$ carbonation reaction. However, the results of this study may be inconclusive in determining the feasibility of or comparing the viability of applying these CO_2 mineralisation processes. Mined and crushed serpentinite mineral is transported 100 km from the mine to the mineralisation plant, resulting in CO_2 emissions of 10.3 kg/tonne of CO_2.

An exergy analysis was carried out to optimise the processes applying the results of the exergy analysis in the life-cycle inventory (LCI) models of t**he ÅAU and the NETL processes leads to 517 kg of CO_2eq and 683 kg of CO_2eq of greenhouse gas emissions (in CO_2 equivalents), respectively, for every tonne of CO_2 mineralised.** The processes analysed have been optimised by heat integration using exergy analysis, hence they represent a more efficient technology than in Khoo (2011). The overall environmental saving potential is higher, due to the more efficient process.

The analysis does not compare the environmental impacts to the conventional production of magnesium carbonate, hence no conclusion can be drawn as to how much improvement to the state of technology of carbonate products on the market would be achieved.

The results prove that mineralisation can be environmentally beneficial in terms of GHG emission reduction. The required heat of 400 °C for the process could be supplied via existing heat structures, therefore **the process has the potential to be used within industrial symbiosis.** Considering that large amounts of minerals need to be mined, transported and processed, material indicators, such as RMI and TMR, should be considered to assess the resource efficiency of those technologies.

State of technology for mineralisation

The CCU mineralisation processes using CO_2 and Magnesium or Calcium as reactants must be divided into two classes of processes.

1. Mineralisation Routes with additional mineral mining.

2. Mineralisation Routes without additional mineral mining.

For the first type of processes the metal component (Mg, Ca) of the later formed mineral needs to be mined by the extraction and processing of certain types of silicate minerals. By contrast, for the second type of processes the components are either extracted from waste streams or the CO_2 is used as an extra component for cement, which means that the Ca-carrying mineral is mined anyway.

- **CCU Routes with additional mining**

Styring et al. (2011) gave an overview over potential silicate minerals (olivine, serpentine, wollastonite and basalt) which could serve as a feedstock for the mineralisation process. In their calculations the mass ratio between the rock mass that is needed to be mined and the bonded CO_2 ranges from **1.6 (olivine, kg per kg of CO_2) to 7.1 (Bbsalt)** which means that the **resource intensity could have a high impact on the overall environmental assessment** of the processes. Khoo et al. (2011) made an LCA of the usage of serpentine which is mined in Australia and used for storing the CO_2 emitted by a natural gas plant in Singapore. They found that the effect on the CO_2 emission balance can be positive but at the same time the overall environmental impact (GWP, acidification, human toxicity, energy used) is negative if the entire production chain is viewed and the process efficiency of the carbonation process is less than 100%. This confirmed the results of an earlier LCA by Khoo et al. (2006) which examined the environmental impacts of CO_2 storage via mineralisation. Furthermore, the analysis did not include the further product phases or the emissions of nitrogen gases during the mining operations, which would enlarge the GWP and environmental impacts of the process. Nduagu et al. (2011) concluded in their LCA that the mineralisation of the emitted CO_2 of a coal-fired plant via serpentine mined nearby reduces the CO_2 emissions of the plant by between 32% and 48% but that the process is energy intensive and faces economical barriers. As well as these results, the material, land and water footprints would have to be calculated in any case to get a sufficient assessment of the environmental impacts of these processes (Steinmann et al., 2016).

Another aspect to consider is that none of the given literature provides examples for a certain use of the produced minerals besides the long-term storage of CO_2. Therefore these types of mineralisation processes should be seen as carbon capture and storage processes and be compared to technical alternatives in this field of technology (Bruhn et al., 2016). A classification as CCU process is only given if the product is used afterwards. Markets for magnesium carbonate, which is analysed in Nduagu et al. (2011), exist, but displacement effects and environmental as well as economic competitiveness have to be evaluated to assume that the product can be sold.

- **CCU-Routes without additional mining**

The non-mining mineralisation routes are further developed in the fields of technical and economic feasibility, as well as promising environmental impacts. At the moment there are five different technologies at TRL Levels from seven to nine using $CaCO_3$ based on captured CO_2 either as a calcium carbonate substitute for concrete block aggregates (Carbon8 Systems, 2017) or as an additive to cement (Carbon Cure Technologies Inc., 2017; Solidia Technologies, 2017; Calera Co-operation, 2017; and Carbstone Innovation, 2017). The CO_2 is bound within the concrete due to a carbonation process during the concrete-curing process which can generally be described as follows:

$$CaO + CO_2 + H_2O + \frac{1}{2}O_2 = CaCO_3 + Ca(OH)_2 \tag{1}$$

The source for the CaO is either a standard cement kiln (Meyer et al., 2017), slag from steel furnaces (Quaghebeur et al., 2015), sewage (Calera Co-operation, 2017) or dust residues from a waste incineration plant (Carbon8 Systems, 2017). In case of the use of CaO from a standard cement kiln the net CO_2 emissions of the process remain positive because of the CO_2 emissions and the corresponding energy-related CO_2 emissions of the kiln process:

$$CaCO_3 + \text{thermal Energy (temp. up to 1450 °C)} = CaO + CO_2 \tag{2}$$

Since in the other cases the CaO source is a waste product from different industrial processes, the connection between the CaO production and CO_2 emissions is not well known and further research is necessary to ensure a correct attribution and ecological assessment.

The advantages of these processes are that flue gases can be used, so that a separate CO_2 capture is not necessary, which reduces the total energy intensity. A reduction of GWI, energy and water requirements for magnesium carbonate from aqueous alkaline absorption of carbon dioxide can be achieved (Galvez-Martos et al., 2016), a CO_2-binding potential up to 160 kg/m³ concrete (Quaghebeur et al., 2012) and a substitution of the normally mined and calcinated CaO source with waste material as well as a high volume market for the products are described in the literature. Furthermore, to assess the economic and ecological impacts of these processes via LCA and LCC (life-cycle costing) more data concerning the process parameters (material and energy inputs) is necessary. The market potential for each product can be estimated via an analysis of their technical specifications and the corresponding technical norms (EU standards or DIN), which is followed by a comparison with already existing products with the same specifications and their volumes.

However, in two of the five processes the positive environmental impact is questionable, because of the unresolved destination of toxic waste residues also bound within the material (Veolia Environmental Services, 2013) or the demand for the additional silicate mineral, wollastonite, which possibly has to be mined exclusively for the process (Sada S., 2013).

Mineralisation technologies offer significant potential for CO_2 usage, as the respective demand for cement is large and not expected to decrease significantly in the near future. In addition, the CO_2 is not being released from the structure over its life-time. Concrete based on CCU cement will represent a promising way to utilise CO_2 **once the environmental impact reduction has been proven.**

Concrete is known to take up carbon dioxide during its life-time (Fengming et al., 2016). The process can be enhanced by ‘concrete curing’ (Carbon Cure Technologies Inc., 2017). Concrete curing is applicable without a source for waste or brackish water, hence it represents a utilisation pathway that is applicable wherever concrete is being produced close to a CO_2 source.

Nevertheless, an LCA would be needed to compare the GWI net effect of technical concrete curing to the natural uptake of CO_2 from the atmosphere over the life-time of the concrete.

2.3.5 Comparison of the climate mitigation potential of CCU for the European Union

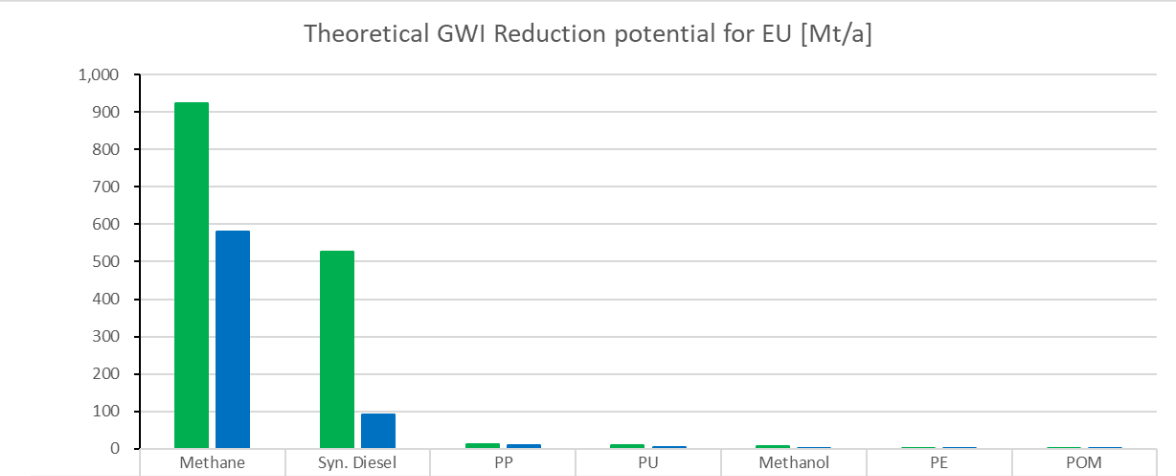
The theoretical climate mitigation potential of CCU technologies was calculated for the EU based on the production and import volume identified in the task 1.1 screening and the GWI reduction per kg of products for the process compared to the conventional process that was identified in Task 1.2 using LCA. The percentage in Table 11 indicates by how much the EU's GWI (Eurostat 2018) could be decreased if the entire EU production and import volume were to be produced from the respective CCU process. Two scenarios are shown in Figure 41. One is the technology performance assuming optimal conditions and the other is assumes the performance yielding the lowest, described environmental benefits:

- the best-case scenario shows the maximum potential based on the technological route with the highest GWI reduction for each product,

- the worst-case scenario is calculated based on the technological route with the lowest GWI reduction potential for each product

It is indicated by how much the EU GWI (Eurostat 2018) could be decreased if the full EU production and import volume would be produced from the respective CCU processes considering the routes with the highest and the lowest GWI reduction. The actual performance of a technology is assumed to be in-between highest and lowest reduction depending on the actual conditions the technology is facing.

Tables and scenario descriptions for the results of the climate mitigation potential of the analysed products based on the LCA can be found in the Appendix, in Chapter 4.4.4: Global warming reduction potentials for the European Union, Table 14 to Table 20. A summary of the results is provided below.



	Methane	Syn. Diesel	PP	PU	Methanol	PE	POM
Best Case	922.4	526.6	13.4	9.8	7.6	2.8	0.2
Worst Case	580.7	92.0	10.9	4.2	2.9	2.2	0.1

Figure 41: Theoretical GWI reduction potential for the EU from replacement of conventional products with carbon neutral products (based on the results of Task 1.1 and Task 1.2)

The results have been sorted by the maximum achievable GWI reduction per product. Other environmental aspects, such as energy storage efficiency, availability of renewable energy and the increase in material and energy consumption, have not been plotted.

With the exception of CO_2-based polyurethane, all other CCU products considered require additional energy, which is assumed to be provided by renewable electricity (otherwise no GWI reduction would result). **All best-case routes, except polyurethanes, include waste-heat utilisation**. **Worst-case routes for hydrogenation routes are mostly based on direct air capture and show an increased demand for heat** for the capturing as described in the LCA. PE/PP were plotted with biogas as a worst-case source, as direct air capture emissions were higher than conventional. For polyurethanes maximum and minimum CO_2 incorporation are assumed.

The ranking in Figure 41 was mainly determined by the volumes of domestic production and imports. Methane is the main compound of natural gas, which is mainly imported and for the most part used for energy purposes. The volume of diesel as transport fuel also clearly exceeds the volume of chemicals production.

As a consequence, methane and synthetic fuels show the highest theoretical effects on climate mitigation. Full replacement of methane production and imports to the EU with a high GWI reduction capture route would make it possible to decrease the GWI for the EU (Eurostat, 2018) by more than 20%, but require more than 840% of the current renewable energy production based on the Energy Roadmap 2015 'CIP' scenario for 2020 (European Union, 2011).

If synthetic fuels are used in the high GWI reduction route with direct air capture and waste-heat utilisation, they could reduce the EU's current GWP by approximately 12%, requiring about 260% of the current renewable energy production.

Synthetic fuels and methanol particularly benefit from waste-heat utilisation. The best-case performance is more than five times higher than the worst-case scenario for synthetic fuels. The best case for methanol is almost three times higher than the worst case. Synthetic fuels production is assumed solely from DAC for both scenarios, hence it benefits from waste heat utilisation.

The other evaluated routes show smaller potential to reduce the EU's GWP (a maximum of 1.3% of the EU's GWI or a minimum of 0.46% of the EU's GWI) due to the smaller EU production and import volume, but individually they could be used to reduce GWI on a regional level or in industry, as long as enough renewable energy is available.

A summary of the results for EU GWI mitigation potential based on the EU total emitted GHG (Eurostat, 2018) is presented in Table 9: GWI reduction, electrical energy demand for the replacement of EU conventional by CO2-based methanol. Required electrical energy is based on electricity used to run the process. For example, electricity that is used to produce process equipment is not included. Data can be found in the LCA-Inventory. The share of renewable electricity is based on EU renewable electricity production of 1,258 TWh/a in 2020 (34.5% of the 3,645 TWh of total electricity production) as assumed in the 'Current Policies Incentive' Scenario of the 'Energy Roadmap 2050' (European Union, 2011).

Table 11: Listed GWI reduction potentials based on replacement of total EU production and import volume with GWI reduction potential for best-case (maximum reduction) and worst-case (minimum reduction) scenarios

Products	EU production & import volume [Mt/a]	Maximum and minimum GWI reduction potential in% of EU GWI	Electricity demand in% of EU renewable electricity production
Methane	367.5	20.96% – 13.20%	842% – 848%
Synthetic diesel	167.2	11.97% – 2.09%	263% – 263%
Polypropylene	11.3	0.31% – 0.25%	26% – 26%
Polyurethanes	3.3	0.22% – 0.09%	Not required
Methanol	8.0	0.17% – 0.07%	7.6% – 7.6%
Polyethylene	2.9	0.06% – 0.05%	6.7% – 6.7%
Polyoxymethylene	0.2	0.004% – 0.003%	NA (see chapter 4.4.4)4.3.4)

2.3.6 Conclusion regarding Task 1.2

The task has been to study the potential of CCU technologies to reduce global warming impact (GWI) for processes with a relevant TRL level. In addition, further aspects, such as regional applicability, energy storage efficiency and integration in the circular economy, have been taken into account. As well as climate impacts, impacts on resource use have also been considered.

A basic challenge of using CO_2 as a raw material is its low energy content. In general, technologies transforming carbon dioxide into energy-rich compounds, such as hydrocarbons, require significant **input of energy**. This input should come from renewable sources, such as wind and solar, otherwise CCU products would have higher environmental impacts than conventional products.

As a consequence, CCU technologies might preferably be applicable in regions with a high potential for renewable energy, in particular electricity. The northern part of Germany is an example of a region with high potential where surplus from wind power could be used. At the same time, the data indicates that relevant amounts of CO_2-based platform chemicals, such as methanol could not be produced from surplus (curtailed) wind power alone: larger amounts of **renewable power** would need to be dedicated to CCU processes.

CO_2-based syngas exhibits a lower efficiency for energy storage if compared to other power storage technologies, such as batteries or hydrogen. However, while batteries deliver only power, CCU products such as syngas provide a **multiple benefit**: energy is stored in a product which can be used for material purposes first and the energy content may be recovered after end of its life.

CCU technologies are particularly important for **carbon recycling**. Chemical recycling is a future focus for the chemical industry and the circular economy. CCU provides chemical transformation options to shift from a linear fossil-based carbon economy to a circular approach using CCU to recycle carbon.

For the chemicals industry CCU technologies can be regarded as key elements to **decouple energy input and raw material supply**. So far carbon and energy have been supplied in combined form, as natural gas and petroleum. In the future energy supply will come from renewable sources while carbon would be increasingly supplied by material recycling (e.g. of plastics) and CO_2 use (e.g. from mixed organic waste).

The study took a closer look at **selected processes**. Most of the analysed processes belong to the 'hydrogenative' route as identified in Task 1.1. These products are well known in the chemicals industry and can be used with the current state of technology. The non-hydrogenative route is exemplified by Covestro's polyurethane production, where CO_2 was successfully introduced to replace an energy-rich educt, so that the CCU process represents an increase in energy efficiency. One may expect that similar options may be found in various energy-intensive production processes in the future; however, if CO_2 is increasingly used to produce hydrocarbons, additional energy supply – from renewables – is inevitable.

Many **potentially promising** CCU technologies are still at an early phase of research and development (e.g. electrochemical and thermochemical routes). Some have proceeded to pilot stage, but data for sufficient LCA is not yet available (e.g. protein production from algae fed with CO_2 from cement kilns or carbon curing).

The aim of our **LCA study** was to identify GHG and resource implications of CO_2-based production routes for a variety of CCU products. The study focused on CO_2-based production of *methane and methanol* as platform chemicals (which can be used for material synthesis as well as transport fuel), the *intermediate synthesis gas,* the commodity polymers *polyethylene (PE) and polypropylene (PP)*, and the specialty polymer *polyoxymethylene (POM) as these are widely representative chemical production routes where data was available.* **Comparative cradle-to-gate analysis** was performed, matching CO_2-based products with conventional fossil-based products.

The results indicate that for methane and methanol production and subsequent synthesis stages, using **cement kilns**, **waste incinerators** and **raw biogas as CO_2-source** could be a promising option for saving GHG emissions. The beneficial use of point sources depends strongly on local conditions, such as availability of **waste heat**. Direct air capture shows the lowest potential to reduce CO_2 emissions, due to the amount of heat required.

In general, greenhouse gas emissions of the studied CO_2-based routes are lower than those of conventionally produced chemicals if wind power is used as a source of electricity. Exceptions are PE and PP produced with DAC. The CO_2 mitigation results mainly from CO_2 input. On the other hand, more material resources are required for the production of CO_2-based chemicals, due to infrastructure requirements for the power input of electrolysis, such as wind turbines. Assessing the trade-off between greenhouse gas emissions and material intensity using the method of normalisation indicates that a higher material intensity may be compensated for by relatively higher savings of GHG emissions. This is not valid for polyolefins produced via the methanol-to-olefins route.

The CO_2 mitigation effect resulting from substitution is **independent of the durability of products (which equals the retention time of the carbon)** for the given product mix. The CO_2 mitigation occurs in the production phase of CCU products. If the type of final products consumed does not change, the existing pattern of short- and long-lived products will remain, and the mitigation effect during production will determine the overall GHG emissions.

At the EU level, producing large shares of chemicals such as methanol (of which there is a total use of about 8 Mt/a) with renewable energy and the studied CO_2 use technologies could lead to a maximum mitigation that is relevant (approximately 7.6 Mt CO_2eq/a), although reducing total GHG emissions by no more than 0.17%, while requiring a substantial amount of renewable power (7.6% of the production foreseen for 2020). It is important to note that CO_2 use for methanol and similar compounds **could not solve the climate issue** but would in the first place **contribute to carbon recycling**.

CO_2-based methane and synthetic fuels show **theoretically the highest effects on climate mitigation**. Full replacement of methane production and imports to EU with a high GWI reduction capture route would make it possible to decrease the EU's GWI (Eurostat, 2018) by more than 20%, but require more than 840% of the current renewable energy production based on the Energy Roadmap 2015 'CIP' scenario for 2020 (European Union, 2011). Synthetic fuels, if used in the high GWI reduction route with direct air capture and waste-heat utilisation, could reduce the current EU GWP by approximately 12%, while requiring about 260% of the current renewable energy production. The other evaluated routes show smaller potentials to reduce the EU GWP (a maximum of 1.3% of the EU's GWI or a minimum of 0.46% of the EU's GWI) due to the smaller EU production and import volume, but individually they can be used to reduce GWI on a regional level or in industry, as long as enough renewable energy is available.

Considering the provision of an adequate supply of renewable power, such as wind, certain routes of CCU using CO_2 as an input may contribute to mitigating climate change pressure while exerting a potentially higher but in relative terms tolerable pressure through material resource flows. The current main challenges are the energy and material demands of electrolysis, and hence costs, which will be required for large-scale production.

From the analysis of different spatial settings of CO_2 capture, hydrogen production for electrolysis and chemical production it can be concluded that the choice of different **transport scenarios has minor influence** on GWI. No relevance was observed for transport up to 50 km. Transporting of hydrogen would be preferable over transporting methane/methanol (due to transport volume). For long distances (500 km) pipeline transport (hydrogen or methane) is preferable over HGV transport (methanol).

When syngas is produced the distribution via different sections of the pipeline grid (low versus high pressure) may determine which kind of use is associated with least GWI. In the example shown **use for chemical synthesis was slightly less climate burdening** than use for car transport.

The energy analysis shows that the direct hydrogenation only yields a reduction in GWI when a high percentage of renewable energy is used. Taking Germany as reference, the percentage of renewable electricity would have to be a **minimum of 86%** in order to reach break-even of CO_2-based with conventional fossil-based products. Effective mitigation would require a higher percentage thereof. The limited availability of renewable energy is a key issue, while CO_2 can be provided in a sufficient quantity.

For **synthetic fuel production from CO_2** it was proven that emission reduction compared to fossil diesel can be achieved. Again, electrical energy from a renewable source is crucial, as overall GHG emissions of the public power grid mix lead to an increase in global warming impact. Thermal energy consumption of direct air capture is another relevant parameter: the GWI reduction is higher if waste heat can be utilised instead of natural gas.

Mineralisation technologies for CO_2 use differ with regard to the requirement for additional mining. When specific minerals are needed to bind CO_2, **1.6 tonne of olivine per tonne of CO_2 to 7.1 tonne of basalt per tonne of CO_2 are required**, which means that varying impacts by mining, transport and resulting waste volumes need to be considered. The spatial distribution of mineral deposits such as olivine are limited. The evaluated LCA can be seen as an indicator that mineralisation processes with additional mining can reduce the CO_2 emissions of a CO_2 point source, but that the efficiency is below a 50%-emission reduction per tonne of CO_2 for the evaluated and already optimised processes.

Mineralisation technologies which **do not directly require additional mining** use CO_2 with waste materials and/or improved process integration. For specific processes, such as those using brine from desalination and aqueous alkaline solutions, improvements in GWI and energy and water consumption have been noted. However, for most of those mineralisation technologies adequate LCA data is not publicly available.

This is also the case for **concrete curing**, a potentially promising technology where flue gas is directly fed into fresh concrete to enhance the binding of its components. This technology could be applied to produce precast concrete elements close to a CO_2 source. A certain mitigation effect seems plausible; however, as concrete also takes up CO_2 by diffusion from the atmosphere during the life-time of the installation, an overall analysis of the net effect is also missing.

Mineralisation routes without additional mining, especially for calcium carbonate, or concrete curing show a high potential GWI reduction, due to the high market demand in Europe, but **more investigation** is needed to analyse the inorganic routes identified in the longlist and shortlist assessment.

Future research may help to elucidate new routes of CO_2 use with a life-cycle-wide efficient use of materials and energy. New technologies, such as high-temperature electrolysis, will have to show their environmental performance in appropriate process networks. Improving the efficiency of the energy-intensive electrolysis process, or even avoiding it, is an outstanding challenge for engineers. Progress towards this goal may finally result in a negative GWI and a low resource input for the production of polymers.

Cross-sectoral analysis should further clarify whether CO_2-based methanol produced with renewable energy could be more efficient used as feedstock for chemical syntheses or as fuel for energetic purposes. For that purpose both the environmental and economic performance of production routes will have to be studied for the complete life-cycle, as utilisation of products may differ between sectors.

2.4 Task 1.3: Market barriers, impacts and opportunities[53]

In this task the manifold implications that a large-scale deployment of CCU technologies could have are identified and discussed. As presented in Section 0 (Task 1.1) of this study, today many CCU technologies are classified as being at an early development stage. While various conversion routes are being explored, and some lab-scale applications already seem promising, the majority of technologies will still need several years before they can approach the relevant markets. Due to this early development stage the levels of uncertainty are still high and it is not possible at this time to perform a meaningful quantitative financial and economic analysis of individual CCU products (see also Hendriks et al., 2013). Instead it is recommended to conduct such on a technology-specific basis for individual projects at this stage.

2.4.1 Market conditions and possible barriers for CCU products and fuels

In this task the manifold implications that a large-scale deployment of CCU technologies could have are identified and discussed. As presented in Section 0 (Task 1.1) of this study, today many CCU technologies are classified as being at an early development stage. While various conversion routes are being explored, and some lab-scale applications already seem promising, the majority of technologies will still need several years before they can approach the relevant markets. Due to this early development stage the levels of uncertainty are still high and it is not possible at this time to perform a meaningful quantitative financial and economic analysis of individual CCU products (see also Hendriks et al., 2013). Instead it is recommended to conduct such on a technology-specific basis for individual projects at this stage.

2.4.2 Market conditions and possible barriers for CCU products and fuels

This Section discusses possible growth perspectives for CCU-based products within existing markets, as well as environmental policy conditions as economic parameters for CCU, and ends by assessing the possible barriers for the further development of CCU.

Possible growth perspectives for CCU technologies in existing markets

From today’s point of view CCU technologies are unlikely to create completely novel products, as technology developers largely try to fit new products to existing markets. In some cases the production process or certain product characteristics change. In any case, product characteristics are the subject of intensive testing and optimisation processes, and most likely to be improved to fit existing product requirements and standards. Some CCU processes, on the other hand, do not alter product characteristics at all, except the environmental parameters, as they solely replace fossil feedstocks with CO_2. The final or intermediate products, for example methanol or polymers, remain chemically unaltered. Consequently, it appears evident to look at current EU production and import volumes of these products as indicators of the potential for CCU-based products (see also Task 1.1). The expectation that the emerging CCU technologies are able to enter existing markets and supply these markets fully can thus be considered as an optimistic long-term scenario.

[53] The considerations about markets, barriers and opportunities are largely based on and excerpting the study ‘CO_2 as an asset – challenges and potential for society’. Olfe-Kräutlein et al, 2016). CO_2 *als Wertstoff - Herausforderungen und Potenziale für die Gesellschaft* Potsdam IASS.

The technology shortlist presented the EU production and import volumes in terms of current supply volumes (production and import) of the selected CCU technologies based on the best available data (see 2.2.2). The shortlisted CCU technologies can be grouped into the following four market clusters:

- polymers (PU, OME1, PA/POM, PE, PP);
- bulk chemicals (methanol, methane, ethylene, propylene, ethanol);
- fuels (synthetic fuels, ethanol, methane, methanol (MeOH)); and
- minerals (sodium carbonate, calcium carbonate).

Continuous **growth in European production** is expected for the market sectors for nine large volume chemicals relevant for CCU within the period until 2050 as depicted in Figure 42 below. This positive outlook is based on a general production growth assumption of 1% p.a. and is subject to many **uncertainties** and connected to **macroeconomic developments** (Bazzanella & Ausfelder, 2017)**.**

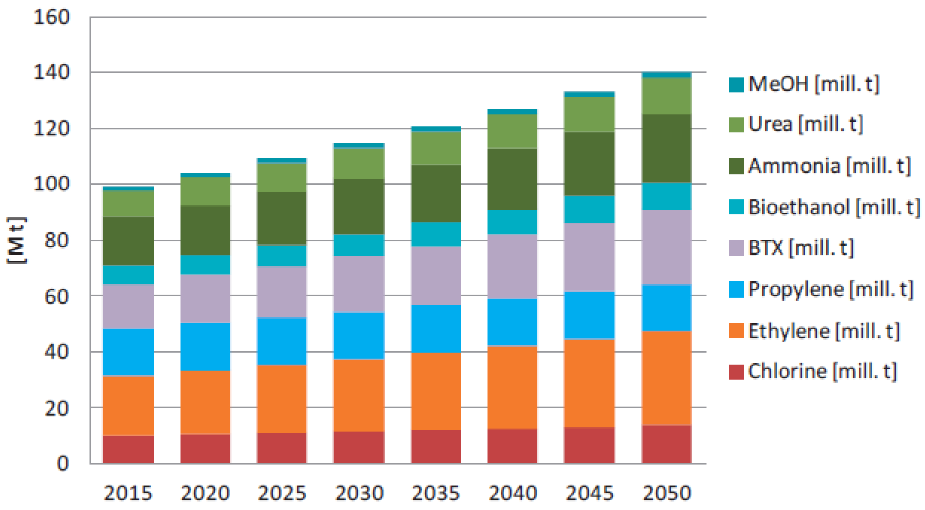


Figure 42: Anticipated European production volumes of nine large volume chemicals (Bazzanella and Ausfelder, 2017)

The extent to which the expected European production volumes of these relevant chemicals and fuels are likely to be CCU-based (as well as bio-based) has also been estimated by the authors, with a continuously increasing share until 2050 (see Figure 43). In order to successfully diffuse on these markets, the CCU-based products need to offer comparable (or improved) quality and competitive pricing. As the CCU-based processes require new production facilities, the demonstration of such plants and their scale-up to industrial size requires several years of preparation. Therefore CCU-based production capacity is likely to remain marginal in the next ten years. A larger scale diffusion in the medium to long term would be connected to very significant investments (see Section 2.4.4).

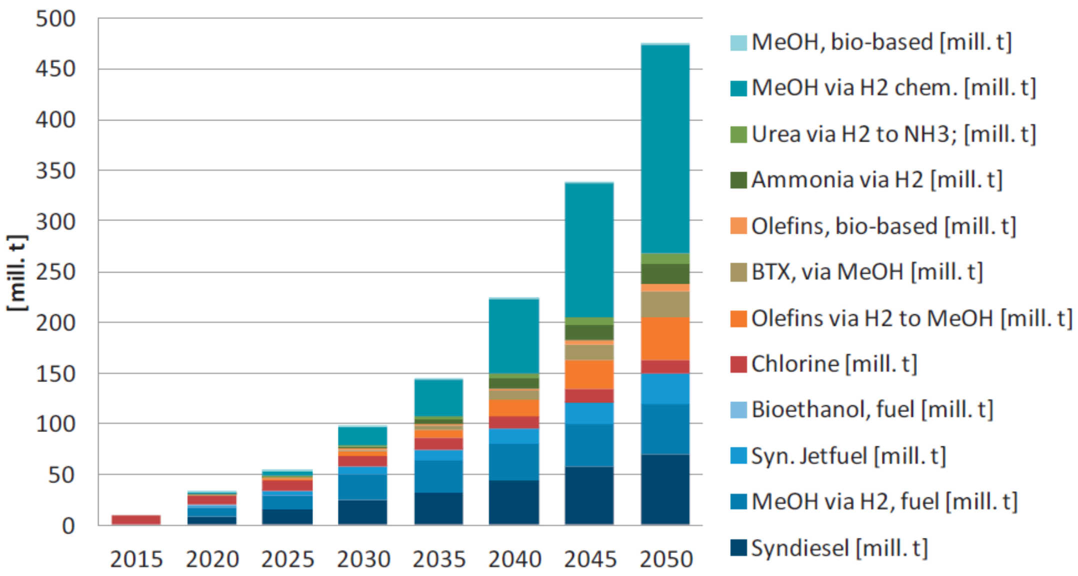


Figure 43: Anticipated maximum CCU- and bio-based production volumes of chemicals and fuels (Bazzanella and Ausfelder, 2017)

Possible barriers for the development of CCU

With regard to the early stage of CCU technologies, the largest barrier to their development is the combined achieving of technical, environmental and economic feasibility, as elaborated on in Sections 2.2 and 2.3 (Tasks 1.1. and 1.2). Furthermore, the source of CO_2 and the provision of renewable energy at a competitive price, as the most influential factors on all CCU technologies, can play a role and have been described in Section 2.3.1 (Task 1.2.1). The future evolution of oil prices can also negatively influence the economic viability of certain CCU applications and inhibit investments in the transition towards renewable energy and CCU applications.

Moreover, some additional barriers are **specific to each CCU application**. In particular, all fuel-related products will strongly depend on policy support (see Section 3, Task 2 for legislation issues). Polymers made with CO_2, for example, seem not to face specific market barriers, since they are connected to efficiency improvements and are economically competitive with conventional polymers. As for all chemicals and materials, CO_2-based products have to be comparable to conventional products in terms of mechanical, physical and chemical performance.

From today's point of view **public objections** are only likely to be met when products made with CO_2 are very close to individuals, for examples in clothes or in cosmetics (Jones et al., 2016). The allegation of CCU being a 'greenwashing' measure for certain industries poses a possible threat in public debates and should thus be addressed with transparent measurement via LCA (see Section 2.3.2). Nevertheless, a barrier in **consumer preferences or in a lack of readiness to pay more** for a 'green' product made with CO_2 cannot be foreseen today (Hendriks et al., 2013; Jones et al., 2016).

The semantic and technological **proximity to CCS**, a technology sometimes rejected by relevant publics (Brunsting et al., 2011), can also pose a barrier for public acceptance (Olfe-Kräutlein et al., 2016) (see also Chapter 2.4.6 below). Therefore the distinction as well as the commonalities between the technologies should be made clear in public and policy-related discourses, in order to avoid possible barriers due to commingling of the two.

2.4.3 Synergy potentials of CCU (industrial symbiosis)

This Section describes potential synergies that could be enabled when CCU technologies are introduced via cross-sectoral collaborations. This is often described by the term and concept 'industrial symbiosis'. Since such collaborations and effects are not unique to the European economy but can be deployed all over the world as suitable local solutions, they need to be studied and planned on the basis of individual projects.

As a sub-discipline of industrial ecology, industrial symbiosis is concerned with resource optimisation among collocated companies (Jacobsen, 2006). With regard to CCU technologies, 'industrial symbiosis' is a key phrase in making them applicable and ecologically worthwhile, as flows of production inputs and outputs are shared among production units. While various approaches exist to pursue industrial symbiosis in theory and practice, such synergies can be achieved through, for example, input and output matching of partners or systemic materials budgeting (Chertow, 2000). Specific to the context of CCU, building synergetic ecosystems has been identified as being useful in overcoming resource shortcomings of individual players (Kant, 2017).

Depending on the specific CCU process, the CO_2-emitting plant is usually not the CO_2-utilising plant. Further involved actors can be providing units of energy and electrolysis. Figure 44 illustrates some potential flows of inputs and outputs, such as CO_2, energy and heat, among those potential actors from the perspective of industrial symbiosis. The specific potential for industrial symbiosis in terms of the involved actors and energy and material flows will be project- and technology-specific and no general quantitative conclusions can be drawn at this point.

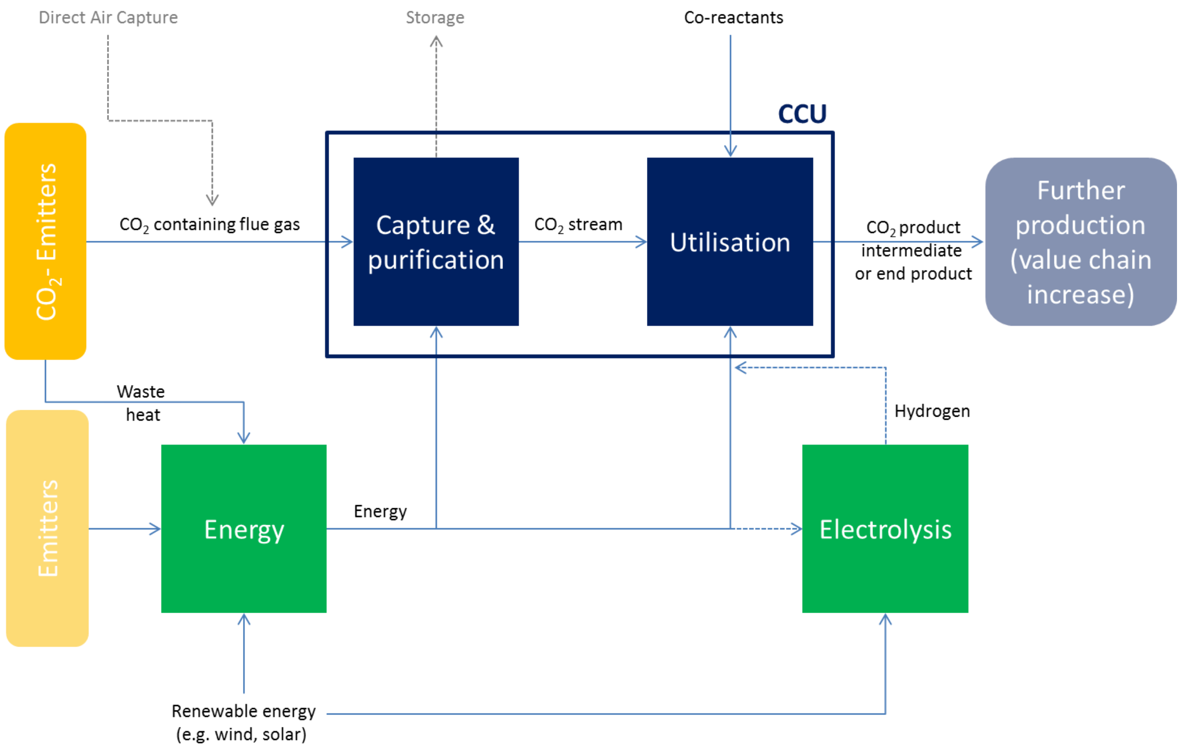


Figure 44: Possible actors within an industrial symbiosis of CCU (IASS)

Cross-industrial co-operation requires the proximity of: a provider of CO_2 of sufficient quality; industrial clients using the CO_2 in their production processes; and, if necessary, a provider of renewable energy or hydrogen and electrolysis (Delft, 2017). Currently candidates for CO_2 **capture** are different industrial plants of various sizes that are connected to CO_2 emissions of different purities and capture costs (Naims, 2016). Other approaches consider biological CO_2 uptake or even direct air capture (DAC) as potential sources of CO_2, but these are currently often not as efficient as the large point sources of CO_2 that are available in industrial regions (von der Assen et al., 2016).

Potential **users of captured CO_2** can be a diverse range of actors, for example producers of chemicals and materials or fuels, such as methanol, DME or TBME, or of different kind of minerals and construction materials.[54]

Moreover, the local availability of renewable energy, which can be decisive for making CCU ecologically worthwhile, can be secured by providing proximity with **energy** producing facilities (e.g. wind or solar energy) or industrial processes that offer **waste heat**. A further unit involved could provide the **electrolysis** if necessary.

In the LCA presented in Section 2.3.4 the highest GWI reduction was achieved, on average, by utilising CO_2 from cement plant and waste incineration power plant sources. These sources use waste heat from the reactions as well as other waste heat (see the Appendix, Table A1, in LCA methodology). Waste-heat utilisation is useful, especially for methanol production or production of synthetic fuels from DAC, as these routes require additional heating energy that is normally provided by natural gas. Waste-heat utilisation has a positive effect on CCU, as energy can be used for the capturing or for direct air capture, if applicable. Future processes, such as high temperature electrolysis used by Sunfire to produce Fischer-Tropsch diesel, also requiresheat to achieve increases in efficiency.

Consequently, the identification of opportunities for industrial symbiosis, clusters of industrial parties and the setting-up of new value chains should be pursued and fostered by policy makers, in research funding schemes and by researchers and developers in order to identify and use possible synergies between point sources, energy sources and potential CO_2 users. As the example of the Carbon2Chem consortium project in Box 1 illustrates, some policy and industrial actors have already anticipated the potential of co-operation in clusters and set up their research and development consortia accordingly (for further examples see also Mennicken et al., 2016).

It is less likely for CCU projects that the involved units will be potentially separated by long distances which would make CO_2 transportation necessary, because that would come at additional costs. Nevertheless, in certain cases this could become necessary when existing plants are considered as retrofit candidates for installing CCU.

Furthermore, it has been stated that the utilisation of possible synergies that increase value and knowledge for the partners involved in CCU often needs the support of intermediating third parties (Kant, 2017). The ability to exploit such synergetic potentials thus requires further support and can be decisive for the economic and ecological feasibility of CCU applications and will gain importance with the growing volume of CCU application.

[54] For more examples of processes that can utilise CO_2 please refer to the technology longlist and shortlist in 1.1.

Box 1: Carbon2Chem: an example for a CCU approach following the vision of 'industrial symbiosis'[55]

Aim of the project

The Carbon2Chem® project aims at using emissions from the production of steel as a raw material, especially CO_2 for the production of valuable chemicals. Energy from renewable sources will be used in the process. The superordinate project goals are to provide a contribution to climate protection and to research energy storage and the stabilisation of the power supply systems.

Co-operating industries

The project involves partners from the chemical and steel industries as well as academic partners, creating an entirely new collaboration between key national industries. The initiator of Carbon2Chem® was ThyssenKrupp (steel production and chemicals). Among the 17 participants are Covestro, Evonik, BASF (chemicals), the Max-Planck Institute and Fraunhofer Gesellschaft (research).

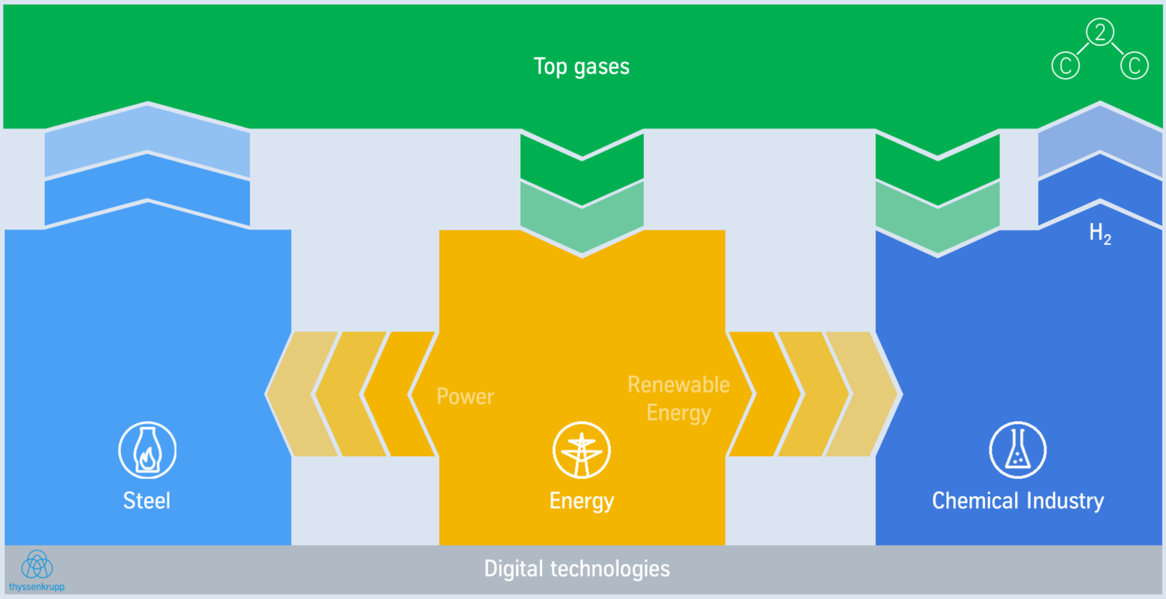


Figure 45: Cross-industrial network of Carbon2Chem (Oles et al., 2018)

Current funding

The German Federal Ministry of Research and Education is providing more than €60 million funding for the project. The partners involved plan to invest more than € 120 million by 2020 and intend to invest more in the second phase of the project.

Expected outcome/products

Carbon2Chem aims to develop, within ten years, a sustainable value chain which interconnects different industry sectors in a cross-industrial network.

[55] Please note that the following project description largely stems from descriptions of the involved industry actors themselves and has not been subject to scientific verification.

Steel mill gases contain 44% nitrogen, 23% carbon monoxide, 21% carbon dioxide, 10% hydrogen and 2% methane. Carbon, hydrogen and nitrogen form the basis for numerous chemical products, such as:

– methanol;

– ammonia and urea;

– higher alcohols;

– polymers; and

– synthetic fuels.

Technological challenges

– Reduction of the CO_2 footprint of hydrogen production

– Volatility and availability of renewable energies

– Performance of catalytic systems

– Gas cleaning and conditioning

Financial and administrative challenges

– Combination and linking of value chains of different industries and optimisation of completely new systems

– Accountability of CCU in terms of CO_2-reduction

– Requirements for new business models (allocation of CO_2 allowances/ETS)

Sources: https://www.thyssenkrupp.com/de/carbon2chem/ as on 8 March 2018 and additional information acquired directly from ThyssenKrupp in the context of stakeholder consultation for this report.

2.4.4 Economic benefits and implications of a larger-scale CCU deployment

This Section discusses possible reciprocal effects between CCU technologies and their specific markets within society on a qualitative basis by considering effects on the central economic fields of European production and regional development, foreign trade, competitiveness and cohesion, investment and financing, as well as employment and household budgets.

In the same way as the previous Section, the following considerations are made on the basis of the assumption of long-term, large-scale, development scenarios for CCU technology with wide-scale manufacture of chemical materials, building materials and fuels on the basis of CO_2, which can be regarded as an optimistic perspective. To reduce the complexity, other and possibly less optimistic scenarios which are included in other more detailed publications (e.g.: Naims, 2016; Piria et al., 2016) are not discussed here.

Possible effects on production within the EU and on regional development

Large-scale CCU might influence industrial production in certain regions of Europe. Depending on technology-specific contributions, new procedures and plants could lead to **reductions of use of fossil raw materials** in the long term, particularly in the chemicals industry. Also, the introduction of CCU technologies could lead to a new and potentially **growing demand for renewable energy** (see also Section 2.3). In addition, the widespread implementation of CCU often requires co-operation beyond the conventional limits of industrial sectors. This results from the necessary co-operation between emitters (for example power stations or steelworks) and potential users (e.g. chemicals plants). Therefore **synergy effects** seem feasible in production through the sharing of knowledge, material or energy flows among industrial units (see also Section 2.4.3 on industrial symbiosis), as does a contribution to a greater structural transformation of industry. As a consequence, the introduction of CCU could lead to **modernisation effects** for European industry (an 'industrial renaissance') (Wilson et al., 2015).

It is also assumed that CCU has the potential to create **economic growth** (Wilson et al., 2015). Whether CCU will have long-term positive effects on produced output and/or GDP growth cannot be clarified with finality on the basis of the knowledge we have today. That will depend on several factors, for example whether CCU-based products replace existing products or whether additional production capacities are created. In this regard additional capacities would have a positive effect on GDP, but from an ecological perspective would be coupled with detrimental **'rebound' effects**. This is due to the fact that more raw materials in total would be used and more products and waste would be produced. These kinds of effects are often regarded and described in the context of increases in efficiency on both the producer side and the consumer side (Santarius, 2012; UBA, 2014).

Possible effects on foreign trade, international competitiveness and cohesion

Current statistics from the European Chemical Association (CEFIC) show that, despite the clear balance-of-trade surplus of the European chemicals industry (in excess of €43.5 billion in 2014), there is a tendency for imports to rise while exports remain constant (CEFIC, 2016). With CCU, CO_2 will be tapped as a new locally available source of raw material, either from industrial waste gas or from the air. Consequently, as an effect on foreign trade the potentially reduced consumption of raw materials could lead to a **reduction of the dependency on imports of fossil resources** in the long term.

The new types of CCU processes, which could lead to valuable technical know-how and several patents, could also imply a **technological advantage** in international competition. This could have a positive effect on export statistics if CCU technologies and products from Europe are demanded and offered on international markets. However, such potential advantages need to be assessed on a technology-specific basis as they move closer to technological, environmental and economic viability.

With regard to **cohesion** inside the EU the potential effects of an introduction of CCU are difficult to foresee. As CCU is very likely to develop potential local solutions of industrial symbiosis and thus is connected to a further concentration of production factors, cohesion could be hampered when the technologies are introduced in existing industrial clusters. On the other hand, CCU could in the long term also allow for more visionary local technological solutions for regions that are more remote and not industrialised yet, e.g. when CO_2 for direct air capture and renewable energy are converted into synthetic fuels.

Possible effects on investment and financing

One potential economic risk could be the **mismanagement of public and private investments in CCU**. Significant losses could occur in specific sectors if CCU processes were coupled with certain conventional industrial plants and, in particular, fossil power-stations as CO_2 sources, which might not be allowed to run anymore in the short- to mid-term for eco-political reasons. These kinds of strategic errors and potential undesired lock-in effects need to be avoided when projects are planned (Olfe-Kräutlein et al., 2016). Instead projects should be considered according to their strategic contribution to European targets.

In addition, economic losses could occur if significant research funding supports technologies that might turn out to be technically or economically unenforceable in the long term or might prove ecologically undesirable. For this reason it is recommended to shape relevant policies as early as possible with a clear vision of technical feasibility and profitability under current / possible future parameters and conditions, as well as to consider positive environmental performance targets, without causing obstacles for basic research (Olfe-Kräutlein et al., 2016).

A large-scale diffusion of CCU technologies would be connected to **very significant investments** from industry in projects which require several years of demonstration and planning. Consequently, regulatory conditions should be reconsidered with regard to enabling **investment security** and reducing potential relevant risks for investors. A recent study shows that investments in CO_2 utilisation are currently discouraged by regulatory uncertainties, a preference for asset-backed investments, and a lack in the development of the market (Kant, 2017). The necessary investments for a large-scale introduction can currently not be quantified, due to a lack of data and the often early development stage. Instead the **investment cost** and respective **financial gap** should currently be assessed on the basis of individual projects.

An overall positive effect in the area of investment financing could, furthermore, be the **founding of businesses** associated with CCU. The results of a global survey show that already more than 50 CCU-related start-ups may have been registered, of which around 40% marketed technologies for fuel production and mineralisation, while around 20% offered chemical products (Zimmermann & Kant, 2016). Entrepreneurship is seen as essential for **Europe's economic growth and the development of jobs, markets and skills** (European Commission, 2018). However, several barriers for new CCU ventures have been pointed out, such as access to institutional investors, which is said to be crucial for scaling-up. Due to the diversity in CCU technologies and geographic contexts, tailored support solutions are recommended (Kant, 2017).

Possible effects on employment and the household budgets

Innovation often leads to the hope for **increases in employment**, an expectation that is also expressed in the case of CCU (Wilson et al., 2015). However, the potential effects of CCU on the number and types of jobs are, at the moment, not foreseeable. They will depend on how and whether the technology becomes industrially established. With regard to the products shortlisted in Section 2, the assumption that creation of new jobs in the fields of research, development and operation of plants is probable in the future would be justified, provided this does not occur in connection with reductions in personnel and shifting of personnel from other areas.

The **income of private households** could be directly influenced by CCU in the event that the level of consumption remains constant and a price difference between CCU-based and conventional products should come about. At the moment, however, it does not seem probable that these products will be offered to consumers at a cheaper price. On the contrary, a higher price seems possible, in particular for technologies that offer properties better for the environment and which, at the same time, are currently more expensive in terms of production than conventional fossil-based products. The decision to buy these kinds of products could, consequently, reduce the income of households while improving their overall environmental performance.

Rebound effects (e.g. increases of material use caused by additional capacities) of CCU products directed at consumers are furthermore indirectly possible, particularly in the relevant segments of chemical products and plastics, building materials and mobility;[56] they are,

[56] In the mobility segment, rebound effects are caused in particular through time savings – this is, however, not influenced by CCU; cp. (Santarius, 2012).

however, not foreseeable, because no cash or time saving for the consumer is to be expected. In any case, such effects would be very difficult to measure.

2.4.5 Interlinkages and path dependencies with energy policies

CCU technologies have the potential to contribute to several EU priorities for modernising the EU's economy, as depicted in Figure 46, especially in the fields of circular economy, innovation, the energy union and climate action. However, one key issue with regard to CCU has proven to be the technologies' fit with existing energy targets and policies (Olfe-Kräutlein et al., 2016). Therefore this Section discusses the inherent interlinkages of the introduction of CCU technologies with the defined energy targets within the EU on a qualitative basis (for quantitative examples see Section 2.3 (Task 1.2)). These interlinkages are identified and discussed in the following Sections via the relevance of the CO_2 source and the possibility of energy storage via CCU.

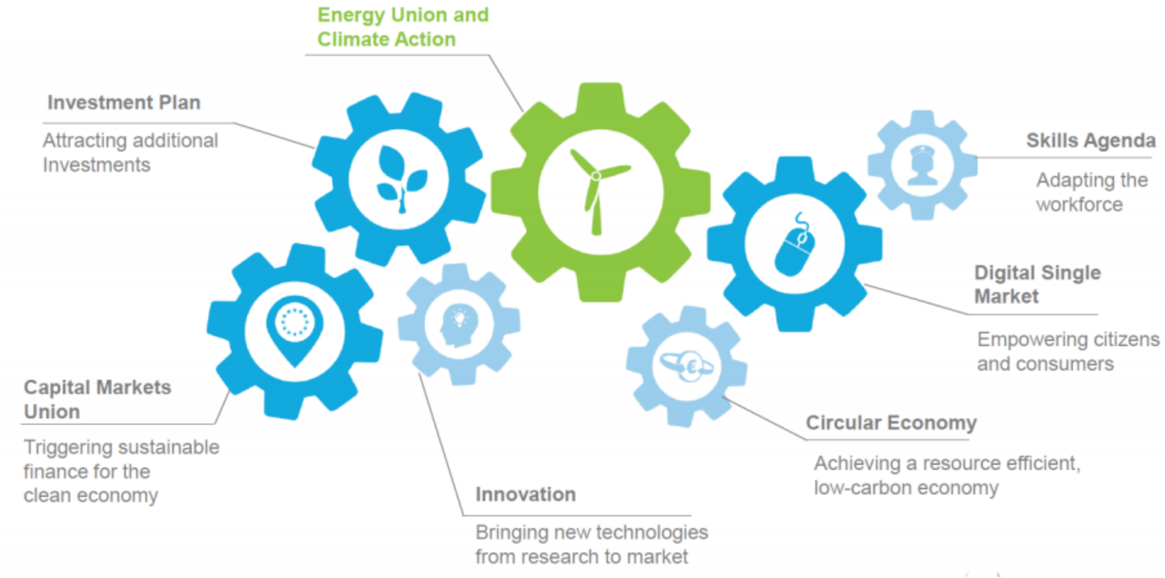


Figure 46: EU priorities to modernise the economy (European Commission, 2016)

The European Commission has defined the **target of lowering by 2030** the carbon intensity of the EU's economy by 43% compared to today's level, while increasing energy efficiency by 30% and the amount of renewable energy to approximately 50% of the electricity generation mix (European Commission, 2016). The interlinkages of CCU with these European energy targets are manifold and depend on the specific broken-down targets and policies of the Member States. The member states could accordingly promote different technological combinations of CCU according to their specific energy policies and industrial infrastructures:

- Certain CCU technologies need energy from renewable sources to deliver a positive environmental performance. Thus **renewable energy strategies and policies are preconditions** for their ecologically worthwhile implementation.
- Furthermore, some CCU applications might be considered as **energy storage** options and thus can be supportive for renewable energy policies by providing flexibility in making use of the volatile supply of energy from renewable sources.
- At the same time, CCU technologies can be considered as an option for policies that aim at **emission reductions from fossil power-generation** when they are designed in combination with the prolongation of conventional coal- or gas-fired power plants.

- Beyond that, very ambitious scenarios which picture a fully **decarbonised economy** suggest the question of whether in their target scenario a sufficient CO_2 supply for CCU technologies can even exist without hindering decarbonisation processes.

CO_2 sources and possible conflicts with energy targets

The aim of all renewable energy policies is to reduce and, as a long-term goal, avoid CO_2 emissions that stem from fossil-based energy production as much as possible. In such ambitious scenarios the comprehensive introduction of CCU technologies could, in the long term, foster a counterproductive 'demand' for CO_2. This could imply '**path dependencies**' which could hinder or delay the abandoning of fossil-based power production and related policies. However, an analysis of possible supply and demand scenarios for CO_2 shows that in the medium term the CO_2 emissions from highly concentrated industrial CO_2 sources are likely to be sufficient to cover CCU purposes, while in the long run other industrial point sources, such as cement plants, will be good and sufficient candidates for CO_2 capture. Unwanted path dependencies thus can be avoided (Naims, 2016).

Looking at the anticipated development of power generation in the EU until 2050 depicted in Figure 47 it becomes evident that the introduction of CCU throughout the EU member states needs to consider such **undesirable lock-in effects** of conventional electricity generation infrastructures, the respective strategies for base-load electricity supply, and necessary plant running times.

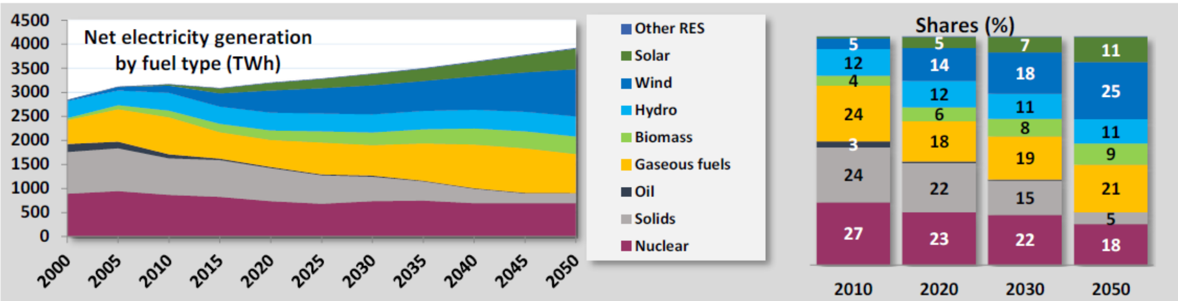


Figure 47: Renewable energy supply projections until 2050 (Capros et al., 2016)

In the long term CO_2 could also be captured from the air, utilising technologies that aim to reduce carbon dioxide that is already in the atmosphere. These currently early development stage technologies can again only contribute to climate protection if the energy necessary for capture and compression of CO_2 comes from renewable sources (Brandani, 2012).

Energy storage with CCU to supplement energy targets

As a molecule CO_2 contains very little energy, all CCU processes that transform the molecule into substances of higher energy require additional energy input when efficiency gains are not possible. Consequently, renewable energy is a necessary input for Power-to-X (PtX) processes (Sternberg & Bardow, 2015; Varone & Ferrari, 2015). The production of such energy carriers is always based on CO_2 and hydrogen, again produced from renewable energy. Interesting novel concepts in this domain have been technically outlined in recent articles on chemical products (Klankermayer & Leitner, 2015), the mobility sector (Varone & Ferrari, 2015), and the aerospace industry (Falter et al., 2016). First demonstration plants in Europe can currently be found in Iceland (CRI) and Germany (Audi).

However, since it is more efficient to use renewable energy directly as electricity in the grid than to convert it into renewable hydrogen and then synthetic carbon-based energy carriers, the potential for introduction of these PtX technologies will be limited due to the overall anticipated share of renewable energy supply in Europe, which is predicted to only reach 56% by 2050 (see Figure 47 (Capros et al., 2016)). Based on those projections, predominantly those regions in Europe with high availability (and fluctuation) of renewable energy are interesting locations for PtX production plants (as '**island solutions**'). Looking at the European map of projected renewable energy supply by 2030 depicted in Figure 48 those countries with the highest shares, which are largely in the north and south, show a relevant potential. For a larger-scale roll-out of PtX across Europe the **share of renewable energy** would have to be significantly increased.[57] Due to the comparatively low prices of fossil fuels, the economic viability of PtX remains challenging and requires creative approaches (e.g. the Audi e-gas card).

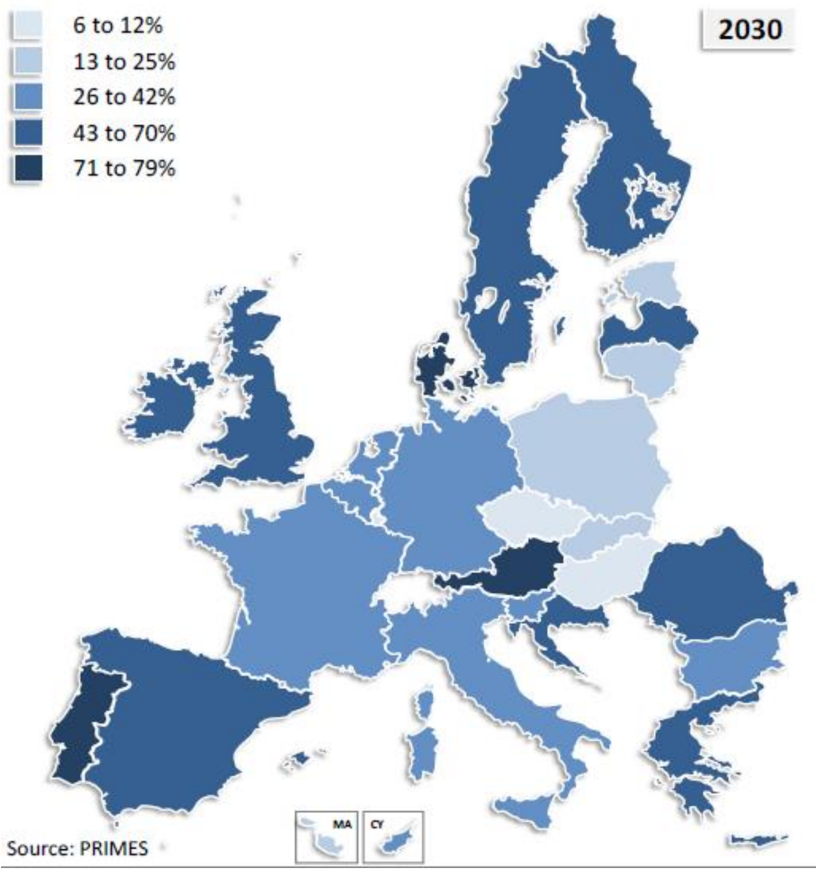


Figure 48: Projected 2030 renewable energy supply shares in EU Member States (Capros et al., 2016)

2.4.6 Public acceptance of CCU technologies

Technical and economic feasibility and measurable ecological advantage are the main drivers of the future development and introduction of CCU technologies. Nevertheless, when approaching a customers' market, different stakeholders' approval of new technologies gains importance and

[57] For example, in the ambitious climate protection vision for a greenhouse-gas neutral Germany set out by the UBA (German Environmental Protection Agency) PtX technologies play a significant role by supplying a base-load of electricity generation and those transport sectors which cannot be electrified (UBA, 2013).

can become decisive for the future fate thereof (Schüwer et al., 2015). Necessary approval includes a broad range of specific stakeholders, but also the approval of the general public (Hampel & Zwick, 2016; Renn, 2005; Wüstenhagen et al., 2007). Examples such as nanotechnologies, genetic engineering, E10 fuel, genetically modified food and CCS technologies demonstrate introduction problems for innovative technologies that are related to a lack of acceptance (Brunsting et al., 2011; Delgado et al., 2011; Hauke, 2014).

The acceptance of CCU products is of specific importance, since CO_2, as the main cause of climate change, is a negatively viewed substance (Van Heek et al., 2017a, 2017b). Furthermore, a co-mingling with CCS technologies, met with rejection in many parts of Europe (Brunsting et al., 2011; Cremer et al., 2008; Schneider, 2017; Selma et al., 2014), might cause negative attitudes towards CCU (Bruhn et al., 2016). This co-mingling can be due to the similarity of the terms, causing mix-ups in terminology, or due to the technical commonalities in the different carbon dioxide capture processes and methods, and can be observed in the media as well as in policy related discourses (Olfe-Kräutlein et al., 2016).

As with other technologies, not only the inherent attributes of the technology, but also a lack of knowledge and familiarity and a feeling of not being well informed can add to a negative perception (van Heek et al., 2017b). Thus, aspects of communication and acceptance have been the object of first scientific studies. A series of studies have analysed the perception of CCU technologies among different groups of individuals (for an overview, please refer to Jones et al., 2017). These are, for example, focus groups composed of students and other volunteers (Jones et al., 2015; Jones et al., 2014), interviews with selected individuals (Jones et al., 2016; Olfe-Kräutlein et al., 2016; Van Heek et al., 2017a, 2017b), a combination of both (van Heek et al., 2017b) or, recently, a first quantitative survey (Perdan et al., 2017).

The results of those studies (i.e. Jones et al., 2017; Perdan et al., 2017; van Heek et al., 2017b) show that awareness and knowledge of CO_2 utilisation is generally low, a result that was expectable given the early development stage of the technology and, consequentially, its limited interaction with the broad public. Nevertheless, in the results of studies with a rather general focus the technology concept itself seems to be convincing (Jones et al., 2016).

However, participants raised doubts about, for example, the technical feasibility of the technologies as well as the long-term environmental benefits. Two exemplary arguments when scrutinising possible investments in CO_2 utilisation are that they could detract from investment in more preferable low-carbon technologies (such as renewables) or conflict with broader sustainability goals, so that CO_2 utilisation is seen by some as being predicated on the continued use of fossil fuels (Jones et al., 2016). Furthermore, participants mentioned the need for a transparent labelling system (Jones et al., 2015; Jones et al., 2016).

Studies with a more market-oriented approach, i.e. focusing on potential customer perceptions of mattresses and plastics made using CO_2, also come to the conclusion that the overall perception is rather positive and risks are generally seen as low (Arning et al., 2017; Van Heek et al., 2017a, 2017b). Here the perceived risks differ slightly, with 'perceived health complaints' and 'disposal conditions' being categorised as main barriers for CCU (van Heek et al., 2017b).

A key shaper of public opinion is the media. Media coverage continues to play an important role in spreading information and raising awareness about technological innovation (Hampel & Zwick, 2016; Weitze & Weingart, 2016). Despite the fact that media coverage is likely to influence the perception of CCU technologies, to date there has been no publication covering the media perception of CCU technologies. This scientific gap thus still needs to be filled.

Based on the knowledge about CCU perception that is available today it can be supposed that large-scale implementation of CCU technologies might face acceptance problems in the context of a co-mingling with CCS technologies. Therefore, as a consequence of what the current research indicates, CCU should be clearly distinguished from CCS technologies when communicating with direct stakeholders and the general public alike, and a differentiation should be made regarding both technologies and contexts. Secondly, concrete ecological effects must be evaluated on the basis of individual technologies and communicated accordingly. Thirdly, a realistic presentation of the possibilities is necessary, in particular, regarding the potential and limitations for CCU to mitigate negative climate and environmental effects in the most diverse and imaginable scenarios.

2.4.7 Conclusion regarding Task 1.3

This Section discussed possible reciprocal effects between CCU technologies and their specific markets within society. The considerations were based on the assumption of long-term, large-scale development scenarios for CCU technologies in various sectors and can be considered as an optimistic perspective.

The societal risks and barriers for introducing CCU technologies, as well as the opportunities they offer are diverse and, to a great extent, technology-specific. Some of them can be influenced by policy measures, others depend on market, technology or other development that cannot be foreseen today.

For example, CCU technologies have the potential **to contribute to various environmental policy aspects**. The current **low prices for fossil resources and energy** provide obstacles for the competitiveness and further development of CCU technology.

Without regulatory support it will not be possible for some technologies to continue competing with cheap fossil materials, although they might seem sensible from an ecological perspective. An **increase in prices of fossil resources and/or availability of renewably produced energy**, at as low a cost as possible, could support the introduction of such technologies. Moreover, further barriers are specific to each CCU application. In particular, all fuel-related products will strongly depend on policy support (see Section 3, Task 2 for legislation issues).

Potential synergies could be enabled when CCU technologies are introduced as cross-sectoral collaborations by way of '**industrial symbiosis**'. The identification of opportunities for industrial symbiosis, clusters of industrial parties and the setting-up of new value chains should be pursued and fostered by policy makers, research funding schemes, and researchers and developers.

It is assumed that CCU can contribute to a modernisation of the industry and also has the potential to create **economic growth** (Wilson et al., 2015). Positive effects on produced output and/or GDP growth cannot be clarified today and will depend on several factors. Detrimental rebound effects, due to increased amounts of products and waste, also need to be taken into account.

One potential economic risk could be the **mismanagement of public and private investments in CCU**. Significant losses could occur in specific sectors if CCU processes were coupled with certain conventional industrial plants and, in particular, **fossil power stations as CO_2 sources**, which are then not allowed to be run in the short- to mid-term for eco-political reasons, or with economically unenforceable or if ecologically undesired technology. Projects should be considered according to their strategic accordance with future European targets.

An overall positive effect in the area of investment financing could, furthermore, be the **founding of businesses** associated with CCU. Entrepreneurship is seen as essential for **Europe's economic growth and the development of jobs, markets and skills** (European Commission, 2018). However, several barriers for new CCU ventures have been pointed out, such as access to institutional investors, which is said to be crucial for scaling-up. Due to the diversity in CCU technologies and geographic contexts tailored support solutions are recommended (Kant, 2017).

Also with regard to European energy targets, the choice of eligible CO_2 sources must be considered in order to avoid path dependencies. Some CCU applications might furthermore be considered as **energy storage** options and thus can be supportive for renewable energy policies. At the same time, CCU technologies can be considered as option for policies that aim at **emission reductions with regard to fossil power generation** when they are designed in combination with the prolongation of conventional coal- or gas-fired power plants.

Looking at the anticipated development of power generation in the EU until 2050 depicted in Figure 47 it becomes evident that the introduction of CCU throughout the EU Member States needs to consider such **undesirable lock-in effects** of conventional electricity generation infrastructures, the respective strategies for base-load electricity supply and necessary plant running times.

Methane and synthetic fuels show **theoretically the highest effects on climate mitigation**. Full replacement of methane production and imports to EU with a high GWI reduction capture route would decrease the EU's GWI (Eurostat 2018) by more than 20%, but would require more than 840% of the current renewable energy production based on the Energy Roadmap 2015 'CIP' scenario for 2020 (European Union 2011). Synthetic fuels, if used in the high GWI reduction route with direct air capture and waste-heat utilisation, could reduce the EU's current GWP by approximately 12%, requiring about 260% of the current renewable energy production. The other evaluated routes show smaller potential to reduce the EU's GWP (a maximum of 1.3% of the EU's GWI or a minimum of 0.46% of the EU's GWI), due to the smaller EU production and import volume, but individually they could be used to reduce GWI on a regional level or in industry, as long as enough renewable energy is available.

Possible policy measures should take these possible effects into account and should be designed accordingly in line with EU policies, also factoring in that it might be necessary to consider policy measures applicable to specific CCU technologies only.

2.5 Summary and conclusions of Task 1

In order to allocate European funding in a worthwhile and efficient way, from both the economic and ecological perspectives, it is necessary to **identify and assess technology applications** that are sufficiently mature regarding their technological development so that they can be expected to be ready for demonstration at pre-commercial scale within the next decade (by 2030) and could possibly **provide an environmental advantage**. As part of this assessment, information has been gathered about projects under development in the EU and worldwide, including their technological readiness, the estimated actual climate and environmental benefits, expected time to commercialisation, the technological advancement necessary to make the technologies economically feasible, their expected timescale, the financial gap for large-scale first-of-a-kind demonstration projects, and their replication potential.

In this regard, the objective of **Task 1.1** was to identify and select promising CCU technologies. Therefore, as a first step, a **longlist of CCU technologies** was provided. The longlist contains an overview of approximately 130 CCU application options and states their respective TRL. It includes chemical routes, assigned to their proposed function in product categories, such as fuels, chemicals or materials; some assigned to more than one category.

Applications with a TRL above 3 were eligible for further assessment and were contained in a preliminary shortlist. The preliminary TRL-related shortlist served as a basis for a multi-criteria assessment, resulting in a shortlist that includes a basic assessment of the selected technologies. The **technology shortlist proposes 15 promising CCU products** and was the basis for the environmental assessment[58] in Task 1.2. It also served as a basis for the

[58] Due to limited data availability only a selection of shortlisted technologies could be assessed in Task 1.2.

regulatory assessment in Task 2. The shortlist adopted the same classification as the longlist and included products from various production routes.

The 15 shortlisted CCU routes are ethanol, methane (biological), ethylene, methane (chemical hydrogenative), methanol, oxymethylene ether (OME1), polyethylene, polyoxymethylene (POM), Polypropylene (PP), propylene, synthetic fuels, polycarbonate (BisA-PC), polyols for polyurethane (PU) foam production, calcium carbonate and sodium carbonate (see also Table 3).

Part of the multi-criteria assessment was an **estimate of the annual CO_2-binding volume** of the shortlisted products, based on the binding potential of the specific chemical formula and a best-case market scenario. According to this estimate, the theoretical total annual CO_2-binding of the shortlisted products amounts to 1,928 Mt of CO_2 per year (see Table 5).

It must be emphasised that although this method is a viable traffic light approach, the data compiled represents estimates in **'ideal case' scenarios** with a 100% utilisation of the binding capacity. In order to make a definite statement on what products and technologies have the largest potential in terms of total emission reductions, a comprehensive LCA of each full process, as well as a detailed market analysis, would have to be conducted. The environmental assessment of selected CCU technologies is described in Section 2.2.

As required in the terms of reference for this report, the assessment based on the aforementioned criteria is a viable approach for identifying promising CCU products and technologies based on their specific TRL and a following multi-criteria assessment. However, the **limited data availability** does not enable one to make a definitive statement on the economic market size of the products. In particular, confidential data, such as financial and cost figures, is generally only available in exceptional cases, and often not comparable, due to insufficient disclosure of assumptions. Costs in relation to market price, however, decide if a technology can survive on the market or if funding or subsidies are necessary. Also, economic, commercial and technology data is highly technology and thus project-specific. Even if for one single project data is available, it cannot be generalised for all products, since economic and environmental data also depend on location, CO_2 input sources, energy supply, etc.

As a consequence, some of the questions in the terms of reference (see Appendix 6) for this report could not be answered sufficiently. Stakeholder interviews that aimed at closing the data gaps in literature only provided project-specific information in some cases, and have not enabled the authors to generalise and to draw conclusions with regard to a certain conversion path or industrial sector. This is in particular the case for the expected time to commercialisation, the technological advantages necessary to make technologies feasible and their timescale, as well as with regard to the question of the financial gap for large first-of-a-kind demonstration projects and the economic conditions. Nevertheless, examples of the answers given have been included in the assessment in Section 2.2.2., concluding that stakeholders stated that for hydrogenate routes, electrolysis for renewable hydrogen production at competitive costs as well as advancements in direct air capture of CO_2 are necessary technological advancements for the successful deployment of CCU technologies. Also, manufacturing scale-up and operational experience were identified as key for large-scale demonstration. Finally, it was stated that the markets as well as society would have to get accustomed to products derived from CO_2.

A standard LCA comparing CCU with conventional products on a cradle-to-gate basis could become a precondition for supporting eligible products, for instance via the Innovation Fund. Eligibility criteria for funding could be that the comparative LCA between the CCU product and the conventional substitute proves a **minimum reduction of GHG emissions of, for instance, 20%**, and **does not lead to relatively higher specific contributions to raw material requirements**. The *relative proportion* of GHG emission reduction and higher raw material requirements would be determined by normalisation to determine the specific contributions: the difference values of Global Warming Impact and Raw Material Input between the CCU and conventional cradle-to-gate values are divided by their economy-wide values for the EU (or a Member State).

The ILCD Handbook General guide on LCA (2010) and several other publications (Hoppe et al., 2017; von der Assen et al., 2013) and initiatives[59] already provide guidance or are preparing proposals for a standardisation of LCA for CCU.

As for other funding options, the current eligibility conditions of financing programmes and instruments under the multi-annual financial framework for the period 2014–2020 in principle offer opportunities for financing CCU projects. These opportunities can be leveraged for CCU projects where these can potentially deliver benefits with regards to, inter alia, innovation, climate action, renewable energy, energy and resource efficiency, in line with the respective objectives of each programme.

The objective of **Task 1.2** was to **determine economic preconditions** (Section 2.3.1) for the shortlisted CCU technologies and to **assess the environmental performance** (Sections 2.3.4 to 2.3.6) for processes where adequate data is available based on the reduction of global warming impact.

As CCU applications differ widely and will be confronted by specific market situations, this report has focused on the major economic preconditions that are vital for the introduction of all CCU technologies, which are CO_2 sources, purity and benchmark costs, and the availability and pricing of renewable energy, in relation to EU energy scenarios.

Many different CO_2 **sources** are suitable for CCU applications. The ideal source will technically depend on the necessary purity of the CO_2, but will also be determined for each application specifically via proximity and price. Several industrial emitters are available as source of high purity CO_2, for example the production of bioethanol and biogas, as it is generally a high purity source of CO_2, or of hydrogen or, at a higher capture cost, also ethylene production or cement plants (for details on CO_2 sources, please refer to Table 6).

The ecological feasibility of many technological options, in particular air capture and PtX (see also Section 2.4.5), relies on the availability of **renewable energy**, and an economic precondition will be its sufficiently low pricing. The EU energy scenarios for 2030 and 2050 project a growing share of **renewable energy** in the energy mix. This development might foster the ecological feasibility of CCU technologies if more renewable energy is produced than required by the energy market. Also, rising and fluctuating oil prices will make CCU technologies more attractive as replacements. CCU technologies themselves can foster advancements towards an energy replacement supply from renewables in terms of combining energy storage with renewable carbon supply.

Previous studies showed that using carbon dioxide (CO_2) as raw material for chemical syntheses may provide an opportunity for achieving greenhouse gas savings and a low-carbon economy. However, the impact of carbon capture and utilisation benefits on the environment in terms of resource requirements and resource efficiency may lead to a trade-off. Therefore **Sections 2.3.2 to 2.3.6 cover a broad environmental framework and LCA for CCU technologies**.

The applied methodology of GHG emission accounting and assessment is described in the IPCC Guidelines for National Greenhouse Gas Inventories (2006) and in the ILCD Handbook – General Guide on LCA (2010). ISO 14040:2006 and ISO 14044:2006 describe the principles and framework for LCA and are used as a methodological reference of LCA. A detailed introduction

[59] For example https://www.iass-potsdam.de/de/forschung/development-guidelines-techno-economic-analysis-tea-co2-conversion-processes

and methods chapter, including data basis as well the supporting information, can be found in the Appendix. The task of the LCA conducted in this report has been to evaluate major environmental impacts and to identify Global Warming Impact (GWI) reduction potentials and resource efficiency implications for the selection of technological routes using a comparative approach and cut-off LCA models with data from ecoinvent 3.1. **A comparative LCA for various CO_2 sources has been conducted on a cradle-to-gate basis and as suggested in the relevant literature for LCA of CCU processes (von der Assenet al., 2013)**. CCU products are compared to their conventional, fossil-based substitutes. The comparative approach makes possible a comparison of technical routes from extraction to production without further consideration of the use and end-of-life phase, because they are identical for the CCU and conventional products and thus do not differ with regard to environmental impacts. **In this LCA final emissions of products are not included, as the emissions are identical for conventional and CO_2-based products. The CCU specific environmental benefit is achieved within the production phase only**. The following diagram shows the origin of the GWI reduction and how CCU affects production:

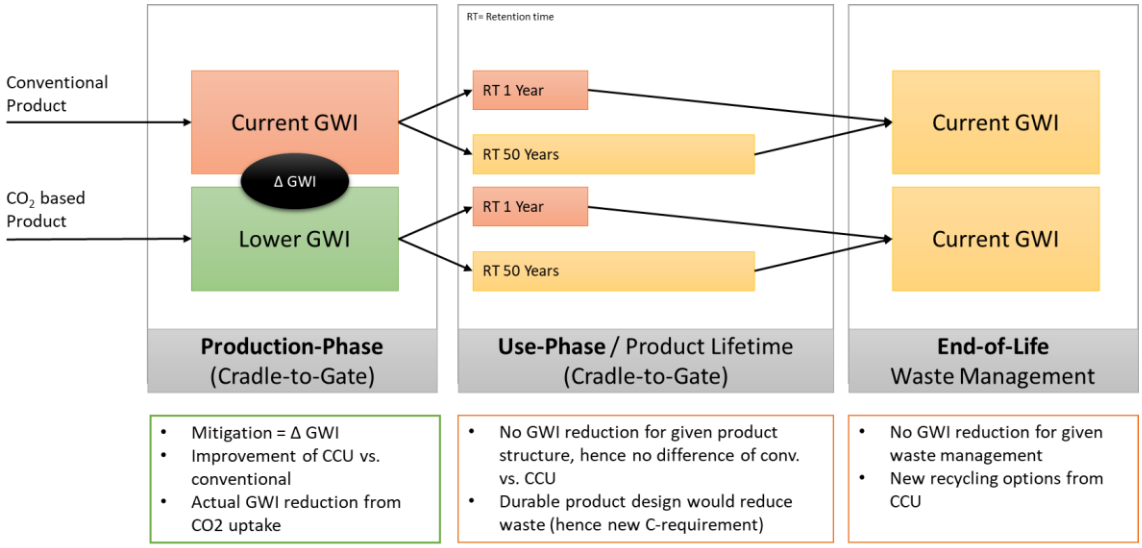


Figure 49: The effects of CCU on the production, use and end-of-life phases for conventional and CO_2-based product life-cycles

Figure 49 summarises the effects of CCU on the production, use and end-of-life phases for conventional and the CO_2-based product life-cycles. The GWI improvement of the CO2-based process over the conventional production with regard to CO_2 uptake and emissions caused by production give a difference in GWI. If the CO2-based process has a lower GWI than the conventional process, an environmental impact reduction can be achieved. Use and end-of-life phases affect the overall GWI of production, but not the difference that is achieved by replacing the conventional production by CCU products.

The CO_2 mitigation effect resulting from substitution is **independent of the durability of products (which equals the retention time of the carbon)** for the given product mix. The CO_2 mitigation occurs in the production phase of CCU products. If the type of final products consumed does not change, the existing pattern of short- and long-lived products will remain, and the mitigation effect during production will determine the overall GHG emissions.

Section 2.3.4 analyses the production of methane and methanol, as basic chemicals, and synthesis gas as intermediate, and derived polyoxymethylene, polyethylene and polypropylene, as polymers, by calculating the output-oriented environmental impact indicator *global warming impact* (GWI) and the resource-based input indicators *raw material input* (RMI) and *total* *material requirement* (TMR) as well as the *cumulative energy demand* (CED) and the water input on a cradle-to-gate basis. As carbon sources this report analyses the capturing of CO_2 from air, raw biogas, cement plants, lignite-fired power and municipal waste incineration plants. Wind power serves as energy source for hydrogen production. Data was derived from both industrial processes and process simulations. Different scenarios were evaluated to find favourable transport routes, first inter-sectoral use analysis or the break-even share of renewable electricity to achieve environmental impact reduction (individual heat sources for capturing are described in the Appendix).

Table 12: Cement plant as CO2 source is assumed to utilise a high share of waste heat and can be used as a benchmark for CCU performance if waste heat can be utilised in an industrial symbiosis.

CO_2-source	Methanation (also for synthesis gas & POM)	Methanol Synthesis (also for PE & PP)
Air	Heat recovery from methanation/natural gas burning	Heat recovery from methanol synthesis/natural gas burning
Biogas	Heat recovery from methanation	Heat recovery from methanol synthesis/natural gas burning
Cement plant	Heat recovery from methanation and kiln exhaust gases	Heat recovery from methanol synthesis and kiln exhaust gases/natural gas burning
Lignite-fired power plant	Work loss of lignite-fired power plant	Work loss of lignite-fired power plant
Waste incineration plant	Work loss of waste incineration plant	Work loss of waste incineration plant

The results indicate that for methane and methanol production, and subsequent synthesis stages, using **cement kilns**, **waste incinerators** and **raw biogas as CO_2 sources** could be a promising option for saving GHG emissions. The beneficial use of point sources depends strongly on local conditions, such as availability of **waste heat**. Direct air capture shows the lowest potential to reduce CO_2 emissions, due to the high demand for heat. Overall, point sources are preferable to direct air capture, as they require less thermal energy, especially if there is waste heat which can be utilised.

Given the provision of an adequate supply of renewable power, certain routes of CCU using CO_2 as input may contribute to mitigating climate change pressure while exerting a potentially higher, but in relative terms tolerable, pressure through material resource flows. This trade-off between decreased greenhouse gas emissions and increased resource use is assessed. The decision about whether to recycle CO_2 into hydrocarbons depends largely on the source and amount of energy used to produce hydrogen. The evaluated routes can only be environmentally beneficial if a large share of renewable or waste energy is used for production.

Greenhouse gas emissions of CO_2-based routes are mostly lower than those of conventionally produced chemicals if wind power is used as the electricity source. On the other hand, more material resources are required for the production of CO_2-based chemicals, due to the power input needed for electrolysis. Assessing the trade-off between greenhouse gas emissions and material intensity indicates that a higher material intensity may be compensated for by relatively higher savings of GHG emissions. This does not apply to polyolefin production via the methanol-to-olefins route.

In conclusion, those products that have the largest CO_2 recycling[60] potential are produced via hydrogenation and thus are dependent on affordable and renewable hydrogen. **The current main challenge is the energy and material demands of electrolysis, and hence costs, which will be required for large-scale production.**

CCU technologies are particularly important for **carbon recycling**. Chemical recycling is a future focus for the chemical industry and the circular economy. CCU provides chemical transformation options to shift from a linear fossil-based carbon economy to a circular approach using CCU to recycle carbon.

For the chemicals industry CCU technologies can be regarded as key elements to **decouple energy input and raw material supply**. So far carbon and energy have been supplied in combined form, as natural gas and petroleum. In the future energy supplies will come from renewable sources, while carbon will be increasingly supplied by material recycling (e.g. of plastics), biomass feedstock and CO_2 use (e.g. from mixed organic waste).

Future research may help to elucidate new routes of CO_2 use with a life-cycle-wide efficient use of materials and energy. New technologies, such as high-temperature electrolysis, will have to show their environmental performance in appropriate process networks. Improving the efficiency of the energy-intensive electrolysis process, or even avoiding it, is an outstanding challenge for engineers. Progress towards this goal may finally, in long-term scenarios, result in a negative GWI and a low resource input for the production of polymers.

Cross-sectoral analysis should further clarify whether CO_2-based methanol produced using renewable energy could be more efficiently used as feedstock for chemical syntheses or as fuel for energetic purposes. For that purpose, both the environmental and economic performance of production routes will have to be studied for the complete life-cycle, as utilisation of products may differ between sectors.

Task 1.3 discusses possible reciprocal effects between CCU technologies and their specific markets and within society. The considerations are based on the assumption of long-term, large-scale development scenarios for CCU technologies in various sectors and can be considered as an optimistic perspective.

Until 2030 CCU technologies are unlikely to create completely novel products, as technology developers largely try to fit new products to existing markets. CCU-based products need to offer comparable (or improved) quality and competitive pricing in order to successfully diffuse on these markets. Due to the early stage of development of most CCU technologies, CCU-based production capacity is likely to remain marginal over the next ten years.

Overall, the societal risks and barriers to introducing CCU technologies, as well as the opportunities they offer, are numerous and diverse and, to a great extent, technology-specific. Some of them can be influenced by policy measures, others depend on market, technology or other development that cannot be foreseen today.

CCU technologies offer the potential to contribute to various environmental policy aspects. The current low prices for fossil resources and energy provide obstacles for the competitiveness and further development of CCU technology. Without regulatory support, it will not be possible for some technologies to continue competing with cheap fossil materials. Although they might seem sensible from an ecological perspective, the environmental benefits of CCU fuel technologies are only being started to be recognised in policy frameworks as of 2021 (also discussed in Task 2/RED II). The environmental benefits of CCU materials technologies are, due to their novelty,

[60] The term ‘binding potential’ is deliberately not used, since the hydrogenation routes lead to products with a low retention time (e.g. fuels, methanol).

not well recognised yet. An **increase in prices for fossil resources and/or availability of renewable electricity and other forms of energy from renewable resources**, at as low a cost as possible, could support the implementation of such technologies. Moreover, further barriers are specific to each CCU application. In particular, all fuel-related products will strongly depend on policy support (see Section3, Task 2 for legislation issues).

Potential synergies could be enabled if CCU technologies are introduced via cross-sectoral collaborations as '**industrial symbiosis**'. This approach can make them applicable and ecologically worthwhile as flows of production inputs and outputs are shared among production units. Potential **users of captured CO_2** can be a diverse range of actors. Moreover, the **local availability** of renewable energy, which can be decisive for making CCU ecologically worthwhile, can be secured by ensuring proximity to **energy** producing facilities (e.g. wind or solar energy) or industrial processes that offer **waste heat**. A further unit involved could provide the **electrolysis** if necessary. Specific in the context of CCU, building synergetic ecosystems has been identified as being useful in overcoming resource shortcomings of individual players (Kant, 2017).

Consequently, the identification of opportunities for industrial symbiosis, clusters of industrial parties and the setting-up of new value chains should be pursued and fostered by policy makers, research funding schemes, and researchers and developers. The specific potential for industrial symbiosis will be project- and technology-specific and no general quantitative conclusions can be drawn at this point.

Large-scale CCU might influence industrial production in certain regions of Europe. Depending on technology specific contributions, new procedures and plants could lead to **reductions of use of fossil raw materials** in the long term, particularly in the chemicals industry. Also, the introduction of CCU technologies could lead to a new and potentially **growing demand for renewable energy** (see also Section 2.4).

It is assumed that CCU can contribute to a modernisation of industry and also has the potential to create **economic growth** (Wilson et al., 2015). Positive effects on produced output and/or GDP growth cannot be clarified today and will depend on several factors. Detrimental rebound effects due to increased amounts of products and waste also need to be taken into account.

As an effect on foreign trade the potentially reduced consumption of raw materials could lead to a **reduction of the dependency on imports of fossil resources** in the long term. The new types of CCU processes which could lead to valuable technical know-how, and several patents could also offer a **technological advantage** in international competition. This could have a positive effect on the export statistics if CCU technologies and products from Europe are demanded and offered on international markets.

With regard to **cohesion** inside the EU the potential effects of an introduction of CCU are difficult to foresee. Local solutions regarding industrial symbiosis might lead to further concentration of production factors and thus hamper cohesion. On the other hand, CCU, for example utilising direct air capture technologies, could in the long term also allow for more visionary local technological solutions for regions that are more remote and not industrialised yet.

One potential economic risk could be the **mismanagement of public and private investments in CCU**. Significant losses could occur in specific sectors if CCU processes were coupled with certain conventional industrial plants and, in particular, **fossil power stations as CO_2 sources**, which are then not allowed to be run in the short- to mid-term for eco-political reasons, or with economically unenforceable or if ecologically undesired technology. Projects should be considered according to their strategic accordance with future European targets.

Also, regulatory conditions should be reconsidered with regard to enabling **investment security** and reducing potential relevant risks for investors.

An overall positive effect in the area of investment financing could, furthermore, be the **founding of businesses** associated with CCU. Entrepreneurship is seen as essential for **Europe's economic growth and the development of jobs, markets and skills** (European Commission, 2018). However, several barriers for new CCU ventures have been pointed out, such as access to institutional investors, which is said to be crucial for scaling-up and first-in-kind projects. Due to the diversity in CCU technologies and geographic contexts, tailored support solutions are recommended (Kant, 2017).

Also with regard to European energy targets, the choice of eligible CO_2 sources must be considered in order to avoid path dependencies. Some CCU applications might furthermore be considered as **energy storage** options and thus can be supportive for renewable energy policies. At the same time, CCU technologies can be considered as option for policies that aim at **emission reductions in fossil power generation** when they are designed in combination with the prolongation of conventional coal- or gas-fired power plants

Looking at the anticipated development of power generation in the EU until 2050 (depicted in Figure 47), it becomes evident that the introduction of CCU throughout the EU Member States needs to consider such **undesirable lock-in effects** of conventional electricity generation infrastructures, the respective strategies for base-load electricity supply and necessary plant running times.

Current studies on the **perception of CCU technologies** do not indicate strong reservations against them. Instead the technologies and their effects tend to be assessed in a positive manner. In order to foster the public acceptance of CCU technologies, and the acceptance of products based on their application, current research suggests distinguishing clearly between CCU and CCS, to integrate LCA results in communication activities and to limit communication activities about the mitigation potential of CCU technologies to realistic scenarios in order to avoid exaggerated expectations.

Overall, the societal risks and barriers to introducing CCU technologies, as well as the opportunities they offer, are numerous and diverse and, to a great extent, technology-specific. Some of them can be influenced by policy measures, others depend on market, technology or other development that cannot be foreseen today. Possible policy measures should take possible effects into account and should be designed accordingly in line with EU policies, also incorporating that it might be necessary to consider policy measures applicable to **specific CCU technologies** only.

2.6 References for Task 1

In the following Section the references are listed according to the given Task so as to enable easier identification of the references. References used in the Appendix are listed here as well.

2.6.1 Reference list for Task 1.1

Bazzanella, A. M., & Ausfelder, F. (2017). Low carbon energy and feedstock for the European chemical industry. Frankfurt am Main

Bruhn, T., Naims, H., & Olfe-Kräutlein, B. (2016). Separating the debate on CO2 utilisation from carbon capture and storage. Environmental Science & Policy, 60, pp.38–43. doi:http://dx.doi.org/10.1016/j.envsci.2016.03.001

EC. (2015). Horizon 2020 Work programme 2014–2015

General Annexes A-K to the main work programme (full document). Brussels Retrieved from http://ec.europa.eu/research/participants/portal/desktop/en/funding/reference_docs.html#doc1

Jung, J., von der Assen, N., & Bardow, A. (2013). Comparative LCA of multi-product processes with non-common products: a systematic approach applied to chlorine electrolysis technologies. The International Journal of Life-cycle Assessment, 18(4), pp.828–839.

Klankermayer, J., & Leitner, W. (2015). Love at second sight for CO2 and H2 in organic synthesis. Science, 350(6261), pp.629–630.

Naims, H. (2016). Economics of carbon dioxide capture and utilisation – a supply and demand perspective. Environmental Science and Pollution Research, 1–16. doi:10.1007/s11356-016-6810-2

Peters, M., Köhler, B., Kuckshinrichs, W., Leitner, W., Markewitz, P., & Müller, T. E. (2011). Chemical Technologies for Exploiting and Recycling Carbon Dioxide into the Value Chain. ChemSusChem, 4(9), 1216–1240. doi:10.1002/cssc.201000447

Piria, R., Naims, H., & Lorente Lafuente, A. M. (2016). CCU: Klimapolitische Einordnung und innovationspolitische Bewertung. Adelphi Discussion Paper. Retrieved from https://www.adelphi.de/en/publications

Styring, P., Jansen, D., de Coninck, H., Reith, H., & Armstrong, K. (2011). Carbon Capture and Utilisation in the green economy. Retrieved from http://co2chem.co.uk/wp-content/uploads/2012/06/CCU%20in%20the%20green%20economy%20report.pdf

Umweltbundesamt (UBA). (2013). Treibhausgasneutrales Deutschland im Jahr 2050 – Hintergrundpapier.

von der Assen, N., Jung, J., & Bardow, A. (2013a). Life-cycle assessment of carbon dioxide capture and utilisation: avoiding the pitfalls. Energy & Environmental Science, 6(9), pp.2721–2734.

von der Assen, N., Jung, J., & Bardow, A. (2013b). Life-cycle assessment of carbon dioxide capture and utilisation: avoiding the pitfalls. Energ. Environ. Sci., 6(9), pp.2721–2734. doi:10.1039/c3ee41151f

von der Assen, N., Lorente Lafuente, A. M., Peters, M., & Bardow, A. (2015). Chapter 4 – Environmental Assessment of CO2 Capture and Utilisation. In K. Armstrong, P. Styring, & E. A. Quadrelli (Eds), Carbon Dioxide Utilisation (pp. 45–56). Amsterdam: Elsevier.

2.6.2 Reference list for Task 1.2

Economical Assessment

Aresta, M., & Dibenedetto, A. (2010). Industrial utilisation of carbon dioxide (CO2). In M. M. Maroto-Valer (Ed.), Developments and innovation in carbon dioxide (CO2) capture and storage technology: Volume 2: Carbon dixide (CO2) storage and utilisation (Vol. 2, pp. 377–410). Great Abington: Woodhead Publishing.

Aresta, M., Dibenedetto, A., & Angelini, A. (2013). The changing paradigm in CO2 utilisation. Journal of CO2 Utilisation, 3, pp.65–73. doi:10.1016/j.jcou.2013.08.001

Arning, K., van Heek, J., & Ziefle, M. (2017). Risk perception and acceptance of CDU consumer products in Germany Paper presented at the 13th International Conference on Greenhouse Gas Control technologies, GHGT-13, Lausanne, Switzerland.

Bazzanella, A. M., & Ausfelder, F. (2017). Low carbon energy and feedstock for the European chemical industry. Frankfurt am Main.

BMWi. (2016). Existenzgründung. Retrieved from http://www.bmwi.de/DE/Themen/Mittelstand/Gruendungen-und-Unternehmensnachfolge/existenzgruendung.html

Bogner, J., Abdelrafie Ahmed, M., Diaz, C., Faaij, A., Gao, Q., Hashimoto, S., Zhang, T. (2007). Waste Management. In B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, & L. A. Meyer (Eds), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 585–618). Cambridge: Cambridge University Press.

Brandani, S. (2012). Carbon dioxide capture from air: a simple analysis. Energy & Environment, 23(2–3), pp.319–328.

Bruhn, T., Naims, H., & Olfe-Kräutlein, B. (2016). Separating the debate on CO2 utilisation from carbon capture and storage. Environmental Science & Policy, 60, pp.38–43. doi:http://dx.doi.org/10.1016/j.envsci.2016.03.001

Brunsting, S., Upham, P., Dütschke, E., Waldhober, M. D. B., Oltra, C., Desbarats, J., Reiner, D. (2011). Communicating CCS: Applying communications theory to public perceptions of carbon capture and storage. International Journal of Greenhouse Gas Control, 5(6), pp.1651–1662.

CEFIC. (2016). Extra-EU chemicals trade balance. The European Chemical Industry: Facts & Figures 2016. Retrieved from http://fr.zone-secure.net/13451/186036/?startPage=13#page=14

European Commission. (2014a). EU ENERGY, TRANSPORT AND GHG EMISSIONS TRENDS TO 2050: REFERENCE SCENARIO 2013.

European Commission. (2014b). A policy framework for climate and energy in the period from 2020 to 2030.

Cremer, C., Esken, A., Fischedick, M., Gruber, E., Idrissova, F., Kuckshinrichs, W., . . . Roser, A. (2008). Sozioökonomische Begleitforschung zur gesellschaftlichen Akzeptanz von Carbon Capture and Storage (CCS) auf nationaler und internationaler Ebene: Endbericht: Wuppertal Institut für Klima, Umwelt, Energie GmbH.

de Coninck, H., & Benson, S. M. (2014). Carbon Dioxide Capture and Storage: Issues and Prospects. Annu. Rev. Env. Resour., 39(1), 243–270. doi:10.1146/annurev-environ-032112-095222

Delft, C. (2017). CCU market options in the Rotterdam Harbour Industrial Complex.

Delgado, A., Lein Kjølberg, K., & Wickson, F. (2011). Public engagement coming of age: From theory to practice in STS encounters with nanotechnology. Public Understanding of Science, 20(6), pp.826–845

European Commission. (2015). Horizon 2020 Work Programme 2014–2015

General Annexes A–K to the main work programme (full document). Brussels. Retrieved from http://ec.europa.eu/research/participants/portal/desktop/en/funding/reference_docs.html#doc1.

Eckl-Dorna, W. (2013, June 28, 2013). Warum Audi auf Öko-Gas setzt, [online]. manager magazin online. Retrieved from http://www.manager-magazin.de/unternehmen/autoindustrie/kuenstliches-erdgas-audis-neue-strategie-fuer-die-autozukunft-a-908172.html

Falter, C., Batteiger, V., & Sizmann, A. (2016). Climate Impact and Economic Feasibility of Solar Thermochemical Jet Fuel Production. Environmental Science & Technology, 50(1), pp.470–477. doi:10.1021/acs.est.5b03515

Hampel, J., & Zwick, M. (2016). Wahrnehmung, Bewertung und die Akzeptabilität von Technik in Deutschland. Technikfolgenabschätzung–Theorie und Praxis, 25. Jg(1).

Hauke, N. (2014). Die grüne Revolution an der Tankstelle? Die Relevanz politischer Narrative am Beispiel der Einführung des Biokraftstoffes E10. In F. Gadinger, S. Jarzebski, & T. Yildiz (Eds), Politische Narrative (pp. 173–197). Wiesbaden Springer.

Hendriks, C., Noothout, P., Zakkour, P., & Cook, G. (2013). Implications of the Reuse of Captured CO2 for European Climate Action Policies. Retrieved from : http://www.scotproject.org/sites/default/files/Carbon%20Count,%20Ecofys%20(2013)%20Implications%20of%20the%20reuse%20of%20captured%20CO2%20-%20report.pdf

IEA. (2014). CO2 emissions from fuel combustion: Highlights. IEA Statistics. Retrieved from https://www.iea.org/publications/freepublications/publication/CO2EmissionsFromFuelCombustionHighlights2014.pdf

Jacobsen, N. B. (2006). Industrial symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects. J. Ind. Ecol., 10(1-2), pp.239–255.

Jilvero, H., Mathisen, A., Eldrup, N.-H., Normann, F., Johnsson, F., Müller, G. I., & Melaaen, M. C. (2014). Techno-economic Analysis of Carbon Capture at an Aluminum Production Plant – Comparison of Post-combustion Capture Using MEA and Ammonia. Energy Procedia, 63, pp.6590–6601. doi:10.1016/j.egypro.2014.11.695

Jones, C., Kaklamanou, D., Stuttard, W., Radford, R., & Burley, J. (2015). Investigating public perceptions of carbon dioxide utilisation (CDU) technology: a mixed methods study. Faraday Discussions, 183, pp.327–347.

Jones, C. R., Olfe-Kraeutlein, B., Naims, H., & Armstrong, K. (2017). The Social Acceptance of Carbon Dioxide Utilisation: A Review and Research Agenda. Frontiers in Energy Research. doi:doi: 10.3389/fenrg.2017.00011

Jones, C. R., Olfe-Kräutlein, B., & Kaklamanou, D. (2016). Lay perceptions of carbon dioxide capture and utilisation technologies in the UK and Germany: a qualitative interview study.

Paper Presented at the 14th International Conference on Carbon Dioxide Utilisation (ICCDU), Sheffield, the UK.

Jones, C. R., Radford, R. L., Armstrong, K., & Styring, P. (2014). What a waste! Assessing public perceptions of Carbon Dioxide Utilisation technology. Journal of CO2 Utilisation, 7, pp.51–54.

Jordal, K., Anantharaman, R., Genrup, M., Aarhaug, T. A., Bakken, J., Lilliestråle, A., . . . Holt, N. J. (2014). Feeding a gas turbine with aluminum plant exhaust for increased CO2 concentration in capture plant. Energy Procedia, 51, pp.411–420. doi:10.1016/j.egypro.2015.03.055

Jung, J., von der Assen, N., & Bardow, A. (2013). Comparative LCA of multi-product processes with non-common products: a systematic approach applied to chlorine electrolysis technologies. The International Journal of Life-cycle Assessment, 18(4), pp.828–839.

Klankermayer, J., & Leitner, W. (2015). Love at second sight for CO2 and H2 in organic synthesis. Science, 350(6261), pp.629–630.

Kurokawa, H., Shirasaki, Y., & Yasuda, I. (2011). Energy-efficient distributed carbon capture in hydrogen production from natural gas. Energy Procedia, 4, pp.674–680. doi:10.1016/j.egypro.2011.01.104

Le Quéré, C., Moriarty, R., Andrew, R., Peters, G., Ciais, P., Friedlingstein, P., Arneth, A. (2014). Global carbon budget 2014. Earth System Science Data Discussions, 7(2), pp.521–610. doi:10.5194/essdd-7-521-2014

Mennicken, L., Janz, A., & Roth, S. (2016). The German R&D Program for CO2 Utilisation – Innovations for a Green Economy. Environmental Science and Pollution Research, pp.1–7. doi:10.1007/s11356–016–6641–1

Metz, B., Davidson, O., De Coninck, H., Loos, M., & Meyer, L. (2005). IPCC special report on carbon dioxide capture and storage. Retrieved from http://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf

Mikkelsen, M., Jorgensen, M., & Krebs, F. C. (2010). The teraton challenge. A review of fixation and transformation of carbon dioxide. Energ. Environ. Sci., 3(1), pp.43–81. doi:10.1039/B912904A

Mueller-Langer, F., Tzimas, E., Kaltschmitt, M., & Peteves, S. (2007). Techno-economic assessment of hydrogen production processes for the hydrogen economy for the short and medium term. Int. J. Hydrogen Energ., 32(16), pp.3797–3810. doi:10.1016/j.ijhydene.2007.05.027

Naims, H. (2016). Economics of carbon dioxide capture and utilisation – a supply and demand perspective. Environmental Science and Pollution Research, pp.1–16. doi:10.1007/s11356-016-6810-2

Olfe-Kräutlein, B., Naims, H., Bruhn, T., & Lorente Lafuente, A. M. (2016). CO2 als Wertstoff – Herausforderungen und Potenziale für die Gesellschaft Potsdam IASS.

Perdan, S., Jones, C. R., & Azapagic, A. (2017). Public awareness and acceptance of carbon capture and utilisation in the UK. Sustainable Production and Consumption, 10, pp.74–84.

Peters, M., Köhler, B., Kuckshinrichs, W., Leitner, W., Markewitz, P., & Müller, T. E. (2011). Chemical Technologies for Exploiting and Recycling Carbon Dioxide into the Value Chain. ChemSusChem, 4(9), pp.1216–1240. doi:10.1002/cssc.201000447

Piria, R., Naims, H., & Lorente Lafuente, A. M. (2016). CCU: Klimapolitische Einordnung und innovationspolitische Bewertung. Adelphi Discussion Paper. Retrieved from https://www.adelphi.de/en/publications

Renn, O. (2005). Technikakzeptanz: Lehren und Rückschlüsse der Akzeptanzforschung für die Bewältigung des technischen Wandels. Technikfolgenabschätzung–Theorie und Praxis, 14(3), pp.29–38.

Roadmap, E. (2011). 2050. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Brussels, 15, 12.

Santarius, T. (2012). Der Rebound-Effekt: Über die unerwünschten Folgen der erwünschten Energieeffizienz.

Schneider, S. (2017). Der öffentliche Diskurs um die geologische Speicherung von Kohlenstoffdioxid (CCS): Strukturgeographische Differenzierungen und ihre Implikationen für die Medienpräsenz wissenschaftlicher Forschung in deutschen Tageszeitungen am Beispiel von CCS (Vol. 7): LIT Verlag Münster.

Schüwer, D., Arnold, K., Bienge, K., Bringezu, S., Echternacht, L., Esken, A., Viebahn, P. (2015). CO2 ReUse NRW: Evaluating gas sources, demand and utilisation for CO2 and H2 within the North Rhine-Westphalia area with respect to gar qualities Retrieved from

Selma, L., Seigo, O., Dohle, S., & Siegrist, M. (2014). Public perception of carbon capture and storage (CCS): A review. Renewable and Sustainable Energy Reviews, 38, 848–863.

Sternberg, A., & Bardow, A. (2015). Power-to-What? – Environmental assessment of energy storage systems. Energ. Environ. Sci., 8(2), 389–400. doi:10.1039/C4EE03051F

Strohbach, O. (2013, June 25, 2013). World premiere: Audi opened power-to-gas facility. Retrieved from http://www.volkswagenag.com/content/vwcorp/info_center/en/themes/2013/06/Audi_opens_power_to_gas_facility.html

Styring, P., Jansen, D., de Coninck, H., Reith, H., & Armstrong, K. (2011). Carbon Capture and Utilisation in the green economy. Retrieved from http://co2chem.co.uk/wp-content/uploads/2012/06/CCU%20in%20the%20green%20economy%20report.pdf

UBA. (2013). Treibhausgasneutrales Deutschland im Jahr 2050 – Hintergrundpapier. Retrieved from Dessau:

UBA. (2014). Rebound-Effekte. Retrieved from https://www.umweltbundesamt.de/themen/abfall-ressourcen/oekonomische-rechtliche-aspekte-der/rebound-effekte

Van Heek, J., Arning, K., & Ziefle, M. (2017a). Differences between laypersons and experts in perceptions and acceptance of CO2-utilisation for plastic products. Paper presented at the 13th International Conference on Greenhouse Gas Control Technologies, GHGT–13, Lausanne, Switzerland.

van Heek, J., Arning, K., & Ziefle, M. (2017b). Reduce, reuse, recycle: Acceptance of CO 2-utilisation for plastic products. Energy policy, 105, pp.53–66.

Varone, A., & Ferrari, M. (2015). Power to liquid and power to gas: An option for the German Energiewende. Renewable and Sustainable Energy Reviews, 45, pp.207–218. doi:http://dx.doi.org/10.1016/j.rser.2015.01.049

VCI, & DECHEMA. (2009, January 12, 2009). Position Paper Utilisation and Storage of CO2. Retrieved from http://www.dechema.de/dechema_media/Positionspapier_co2_englisch-p-2965.pdf

von der Assen, N., Jung, J., & Bardow, A. (2013a). Life-cycle assessment of carbon dioxide capture and utilisation: avoiding the pitfalls. Energ. Environ. Sci., 6(9), pp.2721–2734. doi:10.1039/c3ee41151f

von der Assen, N., Jung, J., & Bardow, A. (2013b). Life-cycle assessment of carbon dioxide capture and utilisation: avoiding the pitfalls. Energy & Environmental Science, 6(9), pp.2721–2734.

von der Assen, N., Lorente Lafuente, A. M., Peters, M., & Bardow, A. (2015). Chapter 4 – Environmental Assessment of CO2 Capture and Utilisation. In K. Armstrong, P. Styring, & E. A. Quadrelli (Eds), Carbon Dioxide Utilisation (pp. 45–56). Amsterdam: Elsevier.

von der Assen, N., Müller, L. J., Steingrube, A., Voll, P., & Bardow, A. (2016). Selecting CO2 Sources for CO2 Utilisation by Environmental-Merit-Order Curves. Environmental Science & Technology, 50(3), 1093-1101. doi:10.1021/acs.est.5b03474

Weitze, M.-D., & Weingart, P. (2016). Schlüsselideen, Akteure und Formate der Technikkommunikation. Technikfolgenabschätzung–Theorie und Praxis, 25 Jg (1).

Wilcox, J. (2012). Carbon capture. New York: Springer.

Wilson, G., Travaly, Y., Brun, T., Knippels, H., Armstrong, K., Styring, P., Bolscher, H. (2015). A VISION for Smart CO2 Transformation in Europe: Using CO2 as a resource.

Wüstenhagen, R., Wolsink, M., & Bürer, M. J. (2007). Social acceptance of renewable energy innovation: An introduction to the concept. Energy policy, 35(5), pp.2683–2691.

Zimmermann, A., & Kant, M. (2016). The Business Side of Innovative CO2 Utilisation. Retrieved from http://enco2re.climate-kic.org/wp-content/uploads/2016/01/The-business-side-of-innovative-CO2-utilisation.pdf

Environmental Assessment

50Hertz Transmission GmbH; Amprion GmbH; TenneT TSO GmbH; Transnet BW GmbH (2016): Netzentwicklungsplan Strom 2025, Version 2015. Zweiter Entwurf der Übertragungsnetzbetreiber.http://www.netzentwicklungsplan.de/_NEP_file_transfer/NEP_2025_2_Entwurf_Teil1.pdf Accessed: 18. Oktober 2016.

Adamek, F.; Aundrup, T.; Glaunsinger, W., Kleimaier, M.; Landinger, H.; Leuthold, M.; Lunz, B.; Moser, A.; Pape, C.; Pluntke, H.; Rotering, N.; Sauer, U.; Sterner, M.; Wellßow, W.

(2012): Energiespeicher für die Energiewende. Speicherungsbedarf und Auswirkungen auf das Übertragungsnetz für Szenarien bis 2050. Verband der Elektrotechnik Elektronik Informationstechnik e.V., Frankfurt a. Main.

Aresta, M., M. Galatola. 1999. Life-cycle analysis applied to the assessment of the environmental impact of alternative synthetic processes. The dimethyl carbonate case. Journal of Cleaner Production 7(3): pp.181–193.

Asinger, F. 1986. Methanol – Chemie- und Energierohstoff: Die Mobilisation der Kohle. [Methanol – feedstock and fuel: The mobilisation of coal.] Berlin: Springer.

Assen, N. von der, Müller, L.J., Steingrube, A., Voll, P., and Bardow, A.. 2016. 'Selecting CO 2 Sources for CO 2 Utilisation by Environmental-Merit-Order Curves.' Environmental Science & Technology 50 (3): pp.1093–1101. doi:10.1021/acs.est.5b03474.

Assen, N. von der, A. Sternberg, A. Kätelhön, and A. Bardow. 2015. Environmental potential of carbon dioxide utilisation in the polyurethane supply chain. Faraday Discussions 183: pp.291–307.

Assen, N. von der and A. Bardow. 2014. Life-cycle assessment of polyols for polyurethane production using CO2 as feedstock: insights from an industrial case study. Green Chemistry 16: pp.3272–3280.

Assen, N. von der, J. Jung, and A. Bardow. 2013. Life-cycle assessment of carbon dioxide capture and utilisation: Avoiding the pitfalls. Energy & Environmental Science 6(9): pp.2721–2734.

bafa (Bundesamt für Wirtschaft und Ausfuhrkontrolle). 2015. Aufkommen und Export von Erdgas: Entwicklung der Grenzübergangspreise ab 1991. [Occurrence and export of natural gas: Cross-border price development as from 1991.] Eschborn, Germany: Bundesamt für Wirtschaft und Ausfuhrkontrolle. http://www.bafa.de/bafa/de/energie/erdgas/ausgewaehlte_statistiken/egasmon.pdf. Accessed February 27, 2015.

Bahn-Walkowiak, B. and S. Steger. 2015. Resource Targets in Europe and Worldwide: An Overview. Resources 4(3): pp.597–620.

BDEW (2015): Erneuerbare Energien und das EEG: Zahlen, Fakten, Grafiken (2015). Anlagen, installierte Leistung, Stromerzeugung, EEG-Auszahlungen, Marktintegration der erneuerbaren Energien und regionale Verteilung der EEG-induzierten Zahlungsströme. Bdew Bundesverband der Energie- und Wasserwirtschaft e.V., Berlin

Benvenuto, M. A. 2014. Industrial Chemistry. Berlin: De Gruyter.

Bertau, M., H. Offermanns, L. Plass, F. Schmidt, and H.-J. Wernicke (Eds), 2014. Methanol: The basic chemical and energy feedstock of the future. Berlin: Springer. Asinger's vision today. http://dx.doi.org/10.1007/978-3-642-39709-7.

BGR (Bundesanstalt für Geowissenschaften und Rohstoffe). 2015. Deutschland – Rohstoffsituation 2014 [Germany – Raw Materials Situation 2014]. Hanover, Germany: Bundesanstalt für Geowissenschaften und Rohstoffe. https://www.bgr.bund.de/DE/Themen/Min_rohstoffe/Downloads/Rohsit-2014.pdf?__blob=publicationFile&v=3. Accessed 06 December, 2016.

Biedermann, P., T. Grube, and B. Höhlein (Eds), 2006. Methanol as an Energy Carrier. In: Schriften des Forschungszentrums Jülich – Reihe Energietechnik, Vol. 55. Jülich, Germany: Forschungszentrum Jülich.

Bilitewski, B. and G. Härdtle. 2013. Abfallwirtschaft. [Waste management.] Berlin, Heidelberg, Germany: Springer Berlin Heidelberg.

BMUB (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit). 2012. Müllverbrennung zur Beseitigung von Abfällen. [Waste incineration as a means to waste disposal.] www.bmub.bund.de/P617/. Accessed 16 November 2015.

BMWi (Bundesministerium für Wirtschaft und Energie). 2016. Zeitreihen zur Entwicklung der erneuerbaren Energien in Deutschland. [Development of renewable energy sources in Germany.] Berlin, Germany: Bundesministerium für Wirtschaft und Energie. http://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/zeitreihen-zur-entwicklung-der-erneuerbaren-energien-in-deutschland-1990-2015.pdf;jsessionid=FDB005FE1E178BBBDF59235665301432?__blob=publicationFile&v=7. Accessed 24 October 2016.

Breuer, C.; Drees, T.; Echternacht, D.; Linnemann, C.; Moser, A. (2012): Standorte und Potenziale für Power-to-Gas. Zeitschrift für Energie, Markt, Wettbewerb, 10 (4), pp.52–55.

Bringezu, S., H. Schütz, and S. Moll. 2003. Rationale for and Interpretation of Economy-Wide Materials Flow Analysis and Derived Indicators. Journal of Industrial Ecology 7(2): pp.43–64.

Bringezu, S & Bleischwitz, R. (2009). Sustainable Resource Management – Global trends, visions and policies. Greenleaf publishing. Sheffield. ISBN-13: 9781906093266

Bruhn, T., H. Naims, and B. Olfe-Kräutlein. 2016. Separating the debate on CO2 utilisation from carbon capture and storage. Environmental Science & Policy 60: pp.38–43.

BTS, RWTH-ITMC, RWTH-LTT, TU Dresden, Uni Stuttgart, TU Darmstadt, TU Dortmund et al., 2014. Schlussbericht CO2RRECT. [Final report CO2RRECT.] BTS; RWTH-ITMC; RWTH-LTT; TU Dresden; Uni Stuttgart; TU Darmstadt; TU Dortmund; Ruhr-Uni-Bochum; LIKAT; FHI Berlin; MPI Magdeburg; KIT; BMS; RWE; Siemens; INVITE. http://edok01.tib.uni-hannover.de/edoks/e01fb14/792621247.pdf. Accessed 22 October 2014.

Bundesnetzagentur. 2016. 3. Quartalsbericht 2015 zu Netz- und Systemsicherheitsmaßnahmen. [3rd quarterly report on network and system security-measures.] Bonn, Germany: Bundesnetzagentur. http://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Allgemeines/Bundesnetzagentur/Publikationen/Berichte/2016/Quartalsbericht_Q4_2015.pdf?__blob=publicationFile&v=1. Accessed 27 October 2016.

Bundesregierung (2010): Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung. Bundesregierung, Berlin. http://www.bundesregierung.de/ContentArchiv/DE/Archiv17/_Anlagen/2012/02/energiekonzept-final.pdf?__blob=publicationFile&v=5. Accessed: 18. October 2016.

Burghart, F. (2014): Einspeisung von Biomethananlagen. Personal note via E-Mail dd. 30 July 2014

Calera Cooperation (Hg.) (2017a): Calera Cooperation – The process. Online verfügbar unter http://www.calera.com/beneficial-reuse-of-co2/process.html, Accessed 24 January 2018.

Calera Coperation (Hg.) (2017b): Basics of Calera Process, Accessed 19 October 2017.

Carbon Cure Technologies Inc. (Hg.) (2017): Carbon Cure Technology. Online verfügbar unter http://carboncure.com/technology/, Accessed 24 January 2018.

Carbon8 Systems (Hg.) (2017): Carbon8 Systems Technology. Online verfügbar unter http://c8s.co.uk/technology/, Accessed 24 January 2018.

Carbstone Innovation (Hg.) (2017): Carbstone Technology. Online verfügbar unter https://www.carbstoneinnovation.be/en/carbstone-innovation-nv-technology2/carbstone-innovation-nv-carbonation, Accessed 24 January 2018.

Climeworks AG (2015): Climeworks. Capturing CO2 from air. Zürich (Schweiz). http://www.climeworks.com/. Accessed 10 August 2015.

Wijkman, Anders, and Kristian Skånberg. 2015. 'The Circular Economy and Benefits for Society: Jobs and Climate Clear Winners in an Economy Based on Renewable Energy and Resource Efficiency.' The Club of Rome, 59. http://www.clubofrome.org/cms/wp-content/uploads/2015/10/The-Circular-Economy-and-Benefits-for-Society.pdf.

Collet, P., E. Flottes, A. Favre, L. Raynal, H. Pierre, S. Capela, and C. Peregrina. 2016. Techno-economic and Life-cycle Assessment of methane production via biogas upgrading and power to gas technology. Applied Energy. In press.

Cuéllar-Franca, R. M. and A. Azapagic. 2015. Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life-cycle environmental impacts. Journal of CO2 Utilisation 9(82): pp.82-102.

Dai, P., Y. Ge, Y. Lin, S. Su, and B. Liang. 2013. Investigation on characteristics of exhaust and evaporative emissions from passenger cars fueled with gasoline/methanol blends. Fuel 113: pp.10–16.

DESTATIS (Statistisches Bundesamt). 2014. Umwelt: Abfallentsorgung. [Environment. Waste disposal.] Fachserie 10, Reihe 1. Wiesbaden, Germany: DESTATIS. https://www.destatis.de/DE/Publikationen/Thematisch/UmweltstatistischeErhebungen/Abfallwirtschaft/Abfallentsorgung2190100127004.pdf?__blob=publicationFile. Accessed 16 November, 2015.

DESTATIS (Statistisches Bundesamt). 2016. Material, Rohstoffe, Wasser: Erstmaliges Aufkommen in Rohstoffäquivalenten in Millionen Tonnen. [Materials, resources, water. Initial volume of raw materal equivalents in million tons.] www.destatis.de/DE/ZahlenFakten/GesamtwirtschaftUmwelt/Umwelt/UmweltoekonomischeGesamtrechnungen/MaterialEnergiefluesse/Tabellen/ErstmaligesAufkommen.html. Accessed 13 April 2016.

(DIN 2006a) Deutsches Institut für Normung e.V.. 2006. Standard: Environmental management – Life-cycle assessment – Requirements and guidelines (ISO 14044:2006); German and English version EN ISO 14044:2006

(DIN 2006b) Deutsches Institut für Normung e.V.. 2006.Standard: Environmental management – Life-cycle assessment – Principles and framework (ISO 14040:2006); German and English version EN ISO 14040:2006

(DIN 2016)- Deutsches Institute für Normung e.V.. 2016. Standard: Environmental management – Water footprint – Principles, requirements and guidelines (ISO 14046:2014); German and English version EN ISO 14046:2016

Deutsches Kupferinstitut. 2006. Kupfer – Werkstoff der Menschheit [Copper – Mankind's Raw Material]. Düsseldorf: Deutsches Kupferinstitut. http://copperalliance.de/docs/librariesprovider4/kupfer-werkstoff-der-menschheit-pdf.pdf?Status=Master&sfvrsn=0. Accessed 06 December, 2016.

DVGW (Deutscher Verein des Gas- und Wasserfaches e.V.). 2013. Technische Regel – Arbeitsblatt: Gasbeschaffenheit. [Technical Guideline – Worksheet: Gas Quality.] DVGW G 260 (A). Bonn, Germany: Deutscher Verein des Gas- und Wasserfaches e.V.

(EASAC 2015) European Academies Science Advisory Council. 2015. Circular Economy: commentary from the perspectives of natural and social sciences

(EASAC 2016) European Academies Science Advisory Council. 2016. Indicators for a Circular Economy. http://www.easac.eu/home/reports-and-statements/detail-view/article/circular-eco-1.html.

(EC 2015) European Commission. 2015. Closing the loop – an EU action plan for the circular economy

(EC 2017) European Commission. 2017. 'Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions – on the Implementation of the Circular Economy Action Plan.' Official Journal of the European Union COM(2017) (33): pp.1–14.

(EEA 2016) European Environment Agency. 2016. More from less: Material resource efficiency in Europe. EEA Report 10/2016. Copenhagen, Denmark: European Environment Agency.

Element Energy Ltd., Carbon Counts Ltd., PSE Ltd., Imperial College, and University of Sheffield. 2014. Demonstrating CO2 capture in the UK cement, chemicals, iron and steel and oil refining sectors by 2025: A Techno-economic Study: Final report for DECC and BIS. Cambridge: Element Energy Ltd.; Carbon Counts Ltd.; PSE Ltd.; Imperial College; University of Sheffield. www.gov.uk/government/uploads/system/uploads/attachment_data/file/311482/Element_Energy_DECC_BIS_Industrial_CCS_and_CCU_final_report_14052014.pdf. Accessed 20 January 2016.

(EMF 2016) Ellen MacArthur Foundation. 2016. 'Intelligent Assets: Unlocking the Circular Economy Potential.' Ellen MacArthur Foundation, 1–25. http://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_Intelligent_Assets_080216.pdf.

Engin, T. and V. Ari. 2005. Energy auditing and recovery for dry type cement rotary kiln systems – A case study. Energy Conversion and Management 46(4): pp.551–562.

ESRL (Earth System Research Laboratory). 2016. Mauna Loa CO2 annual mean data (2015) ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_annmean_mlo.txt. Accessed 3 August, 2016.

European Commission. 2001. Economy-wide material flow accounts and derived indicators: A methodological guide. Luxemburg: Office for Official Publications of the European Communities.

Eurostat (Statistical Office of the European Communities). 2013. Economy-wide Material Flow Accounts (EW-MFA): Compilation Guide 2013. Luxemburg, Luxemburg: Eurostat. http://ec.europa.eu/eurostat/documents/1798247/6191533/2013-EW-MFA-Guide-10Sep2013.pdf/54087dfb-1fb0-40f2-b1e4-64ed22ae3f4c. Accessed 14 April 2016.

Eurostat (Statistical Office of the European Communities). 2018. Climate change – driving forces. http://ec.europa.eu/eurostat/statistics-explained/index.php/Climate_change_-_driving_forces. Accessed 19 February 2018.

Eurostat (Statistical Office of the European Communities). 2017. Material flow accounts – flows in raw material equivalents, accompanying excel file 'Raw material equivalents 2017'. Accessed 19 February 2018

European Union. 2011. 'Energy Roadmap 2050 – Impact Assessment and Scenario Analysis.' Brussels. https://ec.europa.eu/energy/sites/ener/files/documents/roadmap2050_ia_20120430_en_0.pdf.

Fengming, Xi, Davis, Steven J, Ciais, Philippe, Crawford-Brown, Douglas, Guan, Dabo, Pade, Claus, Shi, Tiemao, et al., 2016. 'Substantial Global Carbon Uptake by Cement Carbonation.' Nature Geoscience 9 (12): pp.880–83. doi:10.1038/ngeo2840.

Fischer-Kowalski, M., F. Krausmann, S. Giljum, S. Lutter, A. Mayer, S. Bringezu, Y. Moriguchi, H. Schütz, H. Schandl, and H. Weisz. 2011. Methodology and indicators of economy-wide material flow accounting: State of the art and reliability across sources. Journal of Industrial Ecology 15(6): pp.855–876.

Galvez-Martos, J. L.; Morrison, J.; Jauffret, G.; Elsarrag, E.; AlHorr, Y.; Imbabi, M. S.; Glasser, F. P. (2016): Environmental assessment of aqueous alkaline absorption of carbon dioxide and its use to produce a construction material. In: Resources, Conservation and Recycling 107, S. 129–141. DOI: 10.1016/j.resconrec.2015.12.008.

Gebald, C., J. A. Wurzbacher, P. Tingaut, T. Zimmermann, and A. Steinfeld. 2011. Amine-Based Nanofibrillated Cellulose As Adsorbent for CO2 Capture from Air. Environmental Science & Technology 45(20): pp.9101–9108.

German Biogas Association. 2016. Biogas sector statistics 2015/2016. http://www.biogas.org/edcom/webfvb.nsf/id/DE_Branchenzahlen/$file/16-07-28_Biogas_Branchenzahlen-2015_Prognose-2016_engl_final.pdf. Assessed 3 August 2016.

Götz, M., J. Lefebvre, F. Mörs, A. McDaniel Koch, F. Graf, S. Bajohr, R. Reimert, and T. Kolb. 2016. Renewable Power-to-Gas: A technological and economic review. Renewable Energy 85: pp.1371–1390.

Graedel, T E, J Allwood, J P Birat, M Buchert, C Hageluken, B K Reck, S F Sibley, and G Sonnemann. 2011. 'What Do We Know about Metal Recylcing Rates?' J. Ind. Ecology 15: pp.355–66.

(GWS) GWS mbH. 2011. 'Macroeconomic Modelling of Sustainable Development and the Links between the Economy and the Environment – Final Report.' Osnabrück. doi:http://www.royalcommission.vic.gov.au/finaldocuments/summary/PF/VBRC_Summary_PF.pdf.

Hiremath, Mitavachan, Karen Derendorf, and Thomas Vogt. 2015. 'Comparative Life-cycle Assessment of Battery Storage Systems for Stationary Applications.' Environmental Science and Technology 49 (8): pp.4825–33. doi:10.1021/es504572q.

Hoppe, W., S. Bringezu, and N. Thonemann. 2016. Comparison of global warming potential between conventionally produced and CO2-based natural gas used in transport versus chemical production. Journal of Cleaner Production 121: pp.231–237.

Hoppe, W., N. Thonemann, and S. Bringezu. 2017. 'Life-cycle Assessment of Carbon Dioxide-Based Production of Methane and Methanol and Derived Polymers.' Journal of Industrial Ecology 0 (0). doi:10.1111/jiec.12583.

Hoppe, W. 2018. 'Systemanalytischer Vergleich rohstofflicher Nutzungsoptionen von CO2 bei Verwendung regenerativer Energien unter besonderer Berücksichtigung der Ressourceneffizienz und THG-Bilanz'. Dissertation. University of Kassel. In press, expected publication in 2018.

Hotellier, G. 2014. Hydrogen as a multi-purpose energy vector. https://w3.siemens.com/topics/global/en/events/hannovermesse/program/Documents/pdf/Hydrogen-as-a-multi-purpose-energy%20vector-Gaelle-Hotellier.pdf. Accessed 13 May 2016.

Huijbregts, Mark A J, Stefanie Hellweg, Rolf Frischknecht, Harrie W M Hendriks, Konrad Hungehböhler, and A. Jan Hendriks. 2010. 'Cumulative Energy Demand as Predictor for the Environmental Burden of Commodity Production.' Environmental Science and Technology 44 (6): pp.2189–96. doi:10.1021/es902870s.

(ICEF 2017) Sandalow, David, Roger Aines, Julio Friedmann, Colin McCormick, and Sean McCoy. 2017. 'Carbon Dioxide Utilisation (CO2U) – ICEF Roadmap.' Material provided by the European Union

Icha, P. 2015. Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 bis 2014 [The development of the specific carbon dioxide emissions generated by the German electricity mix from 1990 to 2014]. In: Climate Change. Dessau-Roßlau: Umweltbundesamt.

IEA (International Energy Agency). 2008. CO2 capture in the cement industry: Technical study 2008/3: International Energy Agency Greenhouse Gas R&D Programme. http://ieaghg.org/docs/General_Docs/Reports/2008-3.pdf. Accessed 16 November 2015.

IPCC Guidelines for National Greenhouse Gas Inventories. 2006. 12. https://www.ipcc-nggip.iges.or.jp/public/2006gl/. Accessed 31 January 2017.

Jassim, M. S. and G. T. Rochelle. 2006. Innovative Absorber/Stripper Configurations for CO2 Capture by Aqueous Monoethanolamine. Industrial & Engineering Chemistry Research 45(8): pp.2465–2472.

Jentsch, M. (2015): Potenziale von Power-to-Gas-Energiespeichern. Modellbasierte Analyse des markt- und netzseitigen Einsatzes im zukünftigen Stromversorgungssystem. Dissertation, 2014. Fraunhofer IRB-Verlag, Stuttgart.
Jentsch, M.; Trost, T. (2014): Analyse von Power-to-Gas-Energiespeichern im regenerativen Energiesystem. Teilvorhaben des Verbundprojekts Power-to-Gas - Errichtung und Betrieb einer Forschungsanlage zur Speicherung von erneuerbarem Strom als erneuerbares Methan im 250 kWel-Maßstab. Fraunhofer IWES, Kassel.

Jentsch, M.; Trost, T.; Sterner, M. (2014): Optimal Use of Power-to-Gas Energy Storage Systems in an 85% Renewable Energy Scenario. Energy Procedia, 46, pp.254–261.

JRC. 2010. 'ILCD Handbook – General Guide on LCA.' Edited by European Union. Detailed Guidance. Luxembourg. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC48157/ilcd_handbook-general_guide_for_lca-detailed_guidance_12march2010_isbn_fin.pdf.

Keim, W., ed. 2006. Kunststoffe: Synthese, Herstellungsverfahren, Apparaturen. [Plastics. Synthesis, production process, equipment.] 1. Aufl. Weinheim, Germany: WILEY-VCH.

Kember, M. R. and C. K. Williams. 2012. Efficient Magnesium Catalysts for the Copolymerisation of Epoxides and CO2; Using Water to Synthesise Polycarbonate Polyols. Journal of the American Chemical Society 134(38): pp.15676–15679.

Khoo, H. H., J. Bu, R. L. Wong, S. Y. Kuan, and P. N. Sharratt. 2011. 'Carbon Capture and Utilisation: Preliminary Life-cycle CO2, Energy, and Cost Results of Potential Mineral Carbonation.' Energy Procedia 4: pp.2494–2501. doi:10.1016/j.egypro.2011.02.145.

Khoo, Hsien H.; Tan, Reginald B. H. (2006): Life-cycle Investigation of CO 2 Recovery and Sequestration. In: Environ. Sci. Technol. 40 (12), S. pp.4016–4024. DOI: 10.1021/es051882a.

Klaus, S., M. W. Lehenmeier, C. E. Anderson, B. Rieger. 2011. Recent advances in CO2/epoxide copolymerisation – New strategies and cooperative mechanisms. Coordination Chemistry Reviews 255(13–14): pp.1460–1479.

Klug, K. H. (2010): Grüner Wasserstoff aus Windkraft. Herten baut Windstromelektrolyse-System. HZWEI, 10 (4), pp.16–17.

Langanke, J., A. Wolf, J. Hofmann, K. Böhm, M. A. Subhani, T. E. Müller, W. Leitner, and C. Gürtler. 2014. Carbon dioxide (CO2) as sustainable feedstock for polyurethane production. Green Chemistry 16(4): pp.1865–1870.

Lindner, C., and Hoffmann, O.. 2015. 'Endbericht: Analyse/Beschreibung Der Derzeitigen Situation Der Stofflichen Und Energetischen Verwertung von Kunststoffabfällen in Deutschland.' Düsseldorf. https://www.itad.de/information/studien/ITADConsulticKunststoffstudieApril2015.pdf.

Markewitz, P., W. Kuckshinrichs, W. Leitner, J. Linssen, P. Zapp, R. Bongartz, A. Schreiber, and T. E. Müller. 2012. Worldwide innovations in the development of carbon capture technologies and the utilisation of CO2. Energy & Environmental Science 5(6): pp.7281–7305.

Menanteau, P.; Quéméré, M. M.; Le Duigou, A.; Le Bastard, S. (2011): An economic analysis of the production of hydrogen from wind-generated electricity for use in transport applications. Energy Policy, 39 (5), pp.2957–2965

Meyer V., DeCristofaro N., Bryant J., Sahu S. (2017): Solidia Cement – an example of Carbon Capture and Utilisation. 6th International Converence of Non-Traditional Cement and Concrete. Brno, the Czech Republic, 22 June 2017. Accessed 8 November 2017.

Mike Quaghebeur, Peter Nielsen, Ben Laenen, Dirk Van Mechelen, Evelyne Nguyen (2012): Carbstone: A novel process for the production of construction materials form slags and CO2. Vito – Visions on technology, 2012. Online verfügbar unter https://www.google.de/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0ahUKEwi

S59aQnvDYAhUSZFAKHfOpDtoQFggrMAA&url=http%3A%2F%2Fwww.swedgeo.se%2Fcontentassets%2F0aee8ccd94704620b222156245b2d06d%2Fk1c.-mieke-quaghebeur.pdf&usg=AOvVaw2BblqfDG8aJqgSLAPJ8M4H Accessed 24 January 2018.

Mikkelsen, M., M. Jørgensen, and F. C. Krebs. 2010. The teraton challenge. A review of fixation and transformation of carbon dioxide. Energy & Environmental Science 3(1): pp.43–81.

Moseley, P. T. and J. Garche, ed. 2014. Electrochemical Energy Storage for Renewable Sources and Grid Balancing. Amsterdam: Elsevier.

Moser, P. 2016. Personal communication with P. Moser, Emission Reduction Technologies at RWE Power AG Germany. Email on 2 June 2015.

Mostert, C., Ostrander, B., Bringezu, S., Kneiske, T.M.. 2018. Comparing electrical energy storage technologies regarding their material and carbon footprint, in review, publication expected 2018.

MT-Biomethan GmbH. 2012. Biogasaufbereitungsanlagen. Datenblatt MT-Aminwäsche. [Biogas treatment plants. Data sheet of MT-amine-scrubbing.] Zeven, Germany: MT-Biomethan.

Müller, B., K. Müller, D. Teichmann, and W. Arlt. 2011. Energiespeicherung mittels Methan und energietragenden Stoffen – ein thermodynamischer Vergleich [Energy storage via methane and renewable energy carriers – a thermodynamic comparison]. Chemie Ingenieur Technik 83(11): 2002–2013.

Nduagu, Experience, Joule Bergerson, and Ron Zevenhoven. 2011. 'Life-cycle Assessment of CO2sequestration in Magnesium Silicate Rock – A Comparative Study.' Energy Conversion and Management 55. Elsevier Ltd: pp.116–26. doi:10.1016/j.enconman.2011.10.026.

Nitsch, J.; Pregger, T.; Naegler, T., Heide, D.; Tena, D. de; Trieb, F.; Scholz, Y.; Nienhaus, K.; Gerhardt, N.; Sterner, M.; Trost, T.; Oehsen, A. von; Schwinn, R.; Pape, C.; Hahn, H.; Wickert, M.; Wenzel, B. (2012): Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global. Schlussbericht. Arbeitsgemeinschaft Deutsches Zentrum für Luft- und Raumfahrt (DLR), Stuttgart, Institut für Technische Thermodynamik, Abt. Systemanalyse und Technikbewertung, Fraunhofer Institut für Windenergie und Energiesystemtechnik (IWES), Kassel, Ingenieurbüro für neue Energien (IFNE), Teltow, Stuttgart, Kassel und Teltow.

OECD (Organisation for Economic Cooperation and Development). 2008. Measuring material flows and resource productivity – synthesis report. Paris, France: OECD Publishing.

Olah, G. A., A. Goeppert, and G. K. S. Prakash. 2009. Beyond oil and gas: The methanol economy. 2nd updated and enlarged ed. Weinheim, Germany: WILEY-VCH.

Olah, G. A., G. K. Surya Prakash, and A. Goeppert. 2011. Anthropogenic Chemical Carbon Cycle for a Sustainable Future. Journal of the American Chemical Society 133(33): pp.12881–12898.

Oyenekan, B. A. and G. T. Rochelle. 2006. Energy Performance of Stripper Configurations for CO2 Capture by Aqueous Amines. Industrial & Engineering Chemistry Research 45(8): pp.2457–2464.

Oyenekan, B. A. and G. T. Rochelle. 2007. Alternative Stripper Configurations for CO2 Capture by Aqueous Amines. American Institute of Chemical Engineers Journal 53(12): pp.3144–3154.

Ozbilen, A., I. Dincer, and M. A. Rosen. 2013. Comparative environmental impact and efficiency assessment of selected hydrogen production methods. Environmental Impact Assessment Review 42: pp.1–9.

Pereira, S. R.; Coelho, M. C. (2013): Life-cycle analysis of hydrogen – A well-to-wheels analysis for Portugal. International Journal of Hydrogen Energy, 38 (5), pp.2029–2038.

Peters, M., B. Köhler, W. Kuckshinrichs, W. Leitner, P. Markewitz, and T. E. Müller. 2011. Chemical Technologies for Exploiting and Recycling Carbon Dioxide into the Value Chain. ChemSusChem 4(9): pp.1216–1240.

PlasticsEurope. 2011. Eco-profiles and environmental declarations: LCI methodology and PCR for uncompounded polymer resins and reactive polymer precursor. Version 2.0: PlasticsEurope e.V.

PlasticsEurope, EuPC, EuPR, and EPRO. 2012. Plastics – the Facts 2012: An analysis of European plastics production, demand and waste data for 2011. Brussels, Belgium: PlasticsEurope e.V.; European Plastics Converters (EuPC); European Plastics Recyclers (EuPR); European Association of Plastics Recycling and Recovery Organisations (EPRO). http://www.plasticseurope.org/documents/document/20121120170458-final_plasticsthefacts_nov2012_en_web_resolution.pdf Accessed 17 April 2014.

Quaghebeur, Mieke; Nielsen, Peter; Horckmans, Liesbeth; van Mechelen, Dirk (2015): Accelerated Carbonation of Steel Slag Compacts. Development of High-Strength Construction Materials. In: Front. Energy Res. 3, S. 467. DOI: 10.3389/fenrg.2015.00052.

Quadrelli, E. A., G. Centi, J.-L. Duplan, and S. Perathoner. 2011. Carbon Dioxide Recycling: Emerging Large-Scale Technologies with Industrial Potential. ChemSusChem 4(9): pp.1194–1215.

Reiter, G. and J. Lindorfer. 2015. Global warming potential of hydrogen and methane production from renewable electricity via power-to-gas technology. International Journal of Life-cycle Assessment 20(4): pp.477–489.

Rihko-Struckmann, L. K., A. Peschel, R. Hanke-Rauschenbach, and K. Sundmacher. 2010. Assessment of Methanol Synthesis Utilising Exhaust CO2 for Chemical Storage of Electrical Energy. Industrial & Engineering Chemistry Research 49(21): pp.11073–11078.

Robinius, M. (2016): Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff. Dissertation. Forschungszentrum Jülich, Jülich.

Rochelle, G., E. Chen, S. Freeman, D. Van Wagener, Q. Xu, and A. Voice. 2011. Aqueous piperazine as the new standard for CO2 capture technology. Chemical Engineering Journal 171(3): pp.725–733.

Rostrup-Nielsen, J. and L. J. Christiansen. 2011. Concepts in syngas manufacture. Catalytic science series, vol. 10. London: Imperial College Press. http://site.ebrary.com/lib/alltitles/docDetail.action?docID=10524577

Sada S., DeCristofaro N. (2013): Part one of a two-part series exploring the chemical properties and performance results of sustainable solidia cement and solidia concrete. Hg. v. Solidia Cement. Accessed 8 November 2017.

Saurat, M. and M. Ritthoff. 2013. Calculating MIPS 2.0. Resources 2(4): pp.581–607.

Schaaf, T., J. Grünig, M. Schuster, and A. Orth. 2014. Speicherung von elektrischer Energie im Erdgasnetz – Methanisierung von CO2-haltigen Gasen. [Storage of electricity in the gas grid – methanation of CO2-containing gases.] Chemie Ingenieur Technik 86(4): pp.476–485.

Schäffner, B., M. Blug, D. Kruse, M. Polyakov, A. Köckritz, A. Martin, P. Rajagopalan, U. Bentrup, A. Brückner, S. Jung, D. Agar, B. Rüngeler, A. Pfennig, K. Müller, W. Arlt, B. Woldt, M. Graß, and S. Buchholz. 2014. Synthesis and Application of Carbonated Fatty Acid Esters from Carbon Dioxide Including a Life-cycle Analysis. ChemSuSChem 7(4): pp.1133–1139.

Schandl, H., M. Fischer-Kowalski, J. West, S. Giljum, M. Dittrich, N. Eisenmenger, A. Geschke, M. Lieber, H. P. Wieland, A. Schaffartzik, F. Krausmann, S. Gierlinger, K. Hosking, M. Lenzen, H. Tanikawa, A. Miatto, and T. Fishman. 2016. Global Material Flows and Resource Productivity. An Assessment Study of the UNEP International Resource Panel. Paris, France: United Nations Environment Programme (UNEP).

Schrader, S.; Zehren, D.; Kampik, J., Rummler, M.; Beulertz, D.; Raths, S. (2015): Mittelfristprognose zur deutschlandweiten Stromerzeugung aus EEG geförderten Kraftwerken für die Kalenderjahre 2016 bis 2020. P3 Energy & Storage GmbH, Institut für Hochspannungstechnik, Aachen.

Schüller, M., A. Estrada, and S. Bringezu. 2008. Mapping Environmental Performance of International Raw Material Production Flows: a Comparative Case Study for the Copper Industry of Chile and Germany. Minerals & Energy – Raw Materials Report 23(1): pp.29–45.

Schüwer, D., K. Arnold, S. Bringezu, K. Bienge, A. Esken, M. Fischedick, K. Kamps et al., 2015. CO2 ReUse NRW: Evaluating Gas Sources, Demand and Utilisation for CO2 and H2 within the North Rhine-Westphalia Area with Respect to Gas Qualities. Wuppertal: Wuppertal Institute for Climate, Environment and Energy. http://epub.wupperinst.org/files/6010/6010_CO2_ReUse.pdf. Accessed 10 December, 2015.

Schwab, E., A. Milanov, S. A. Schunk, A. Behrens, and N. Schödel. 2015. Dry Reforming and Reverse Water Gas Shift: Alternatives for Syngas Production? Chemie Ingenieur Technik 87(4): pp.347–353.

Solidia Technologies (2017): Solidia Product Brochure. Where Sustainability meets profitability and performance. Hg. v. Solidia Technologies und Lafarge Holcim. Piscataway. Accessed 7 November 2017.

Spohn, C. 2013. Thermische Abfallbehandlung in Deutschland. [Thermal waste treatment in Germany.] Recycling Almanach, pp.142–143.

Stadler, I.; Sterner, M. (2014): Energiespeicher. Bedarf, Technologien, Integration. Springer Vieweg, Berlin.

Statistik der Kohlenwirtschaft. 2013. Braunkohle im Überblick 1989 – 2014. [An overview of lignite from 1989 to 2014.] http://www.kohlenstatistik.de/files/kw-leistung.xlsx Accessed 15 January 2016.

Steinmann, Z. J. N., A. M. Schipper, M. Hauck, M. A. J. Huijbregts. 2016. How many environmental impact indicators are needed in the evaluation of product life-cycles? Environonmental Science & Technology 50(7): pp.3913–3919.

Sternberg, A. and A. Bardow. 2015. Power-to-What? – Environmental assessment of energy storage systems. Energy & Environmental Science 8(2): pp.389–400.

Styring, P. 2015. Carbon Dioxide Capture Agents and Processes. In Carbon Dioxide Utilisation, edited by P. Styring et al. Amsterdam, The Netherlands: Elsevier Science Ltd.

Styring, P., D. Jansen, H. de Coninck, H. Reith, and K. Armstrong. 2011. Carbon Capture and Utilisation in the green economy: Using CO2 to manufacture fuel, chemicals and materials. Paper presented at Report No. 501. Birmingham, the UK: The Centre for Low Carbon Futures 2011.

Trost, T., S. Horn, M. Jentsch, and M. Sterner. 2012. Erneuerbares Methan: Analyse der CO2-Potenziale für Power-to-Gas Anlagen in Deutschland. [Renewable methane. Analysis of CO2-potentials for power-to-gas plants in Germany.] Zeitschrift für Energiewirtschaft 36(3): pp.173–190.

Trott, G., P. K. Saini, and C. K. Williams. 2016. Catalysts for CO2/epoxide ring-opening copolymerisation. Philosophical Transactions of the Royal Society 374(2061): pp.1–19.

UBA (Umweltbundesamt). 2016. Emissionen von direkten und indirekten Treibhausgasen und von Schwefeldioxid. [Emissions of direct and indirect greenhouse gases and of sulphur dioxide.] Dessau-Roßlau, Germany: UBA. https://www.umweltbundesamt.de/daten/klimawandel/treibhausgas-emissionen-in-deutschland Accessed 13 April 2016.

(UNEP 2009) Bringezu, Stefan, Meghan O Brien, Robert W Howarth, Ulrich Von Weizsäcker, Yvan Hardy, Mercedes Bustamante, Sanit Aksornkoae, Anna Bella, and Jacqueline Mcglade. 2009. Towards Sustainable Production and Use of Resources: Assessing Biofuels Summary. http://books.google.com/books?hl=en&lr=&id=j2tye32GJy0C&oi=fnd&pg=PA23&dq=Towards+sustainable+production+and+use+of+resources+:+Assessing+Biofuels&ots=HQlKc32Eo9&sig=I9TrjCUxLFs8AP-08bAFt8uAlRM

UNEP. (2011). Decoupling natural resource use and environmental impacts from economic growth: a report of the Working Group on Decoupling to the International Resource Panel. Paris.

(UNEP 2014) Bringezu, Stefan, Helmut Schütz, Walter Pengue, Meghan O Brien, Fernando Garcia, Ralph Sims, Robert W Howarth, et al., 2014. Assessing Global Land Use: Balancing Consumption with Sustainable Supply. A Report of the Working Group on Land and Soils of the International Resource Panel. http://www.unep.org/resourcepanel/Portals/50244/publications/Full_Report-Assessing_Global_Land_UseEnglish_(PDF).pdf.

Universität Stuttgart. 2015. 'Verbundprojekt Sunfire Herstellung von Kraftstoffen Aus CO2 Und H2O Unter Nutzung Regenerativer Energie,' 62.

Urban, A. I., ed. 2007. Weiterentwicklung der Abfallwirtschaft: Abfallwirtschaft ohne duale Systeme? [The development of waste management. Waste management without dual systems?] In: Schriftenreihe des Fachgebietes Abfalltechnik/Institut für Wasser, Abfall, Umwelt UNIK-AT, Vol. 7. Kassel, Germany: Kassel Univ. Press.

Vasudevan, S., S. Farooq, I. A. Karimi, M. Saeys, M. C. G. Quah, R. Agrawal. 2016. Energy penalty estimates for CO2 capture: Comparison between fuel types and capture-combustion modes. Energy 103: pp.709–714.

VDZ (Verein Deutscher Zementwerke e.V.). 2013. Verminderung der CO2-Emissionen: Monitoring-Abschlussbericht 1990-2012. [Reducing CO2 emissions. Final monitoring report 1990-2012.] Paper presented at 11. aktualisierte Erklärung zur Klimavorsorge. Düsseldorf, Germany: VDZ https://www.vdz-online.de/fileadmin/gruppen/vdz/3LiteraturRecherche/UmweltundRessourcen/co2monitoring/Monitoring_Bericht_Zement_1990-2012.pdf Accessed 15 January 2015.

VDZ (Verein Deutscher Zementwerke e.V.). 2015. Zementindustrie im Überblick 2015. [An overview of the cement industry in 2015.] Düsseldorf and Berlin, Germany: VDZ.

Veolia Environmental Services (2013): Position Paper: Air Pollution Control Residues. Hg. v. Veolia Environmental Services, Accessed 6 November 2017.

WEG (Wirtschaftsverband Erdöl- und Erdgasgewinnung e.V.). 2015. Jahresbericht 2014/2015. Zahlen und Fakten. [Annual Report 2014/2015. Facts and Figures.] Hannover, Germany: Wirtschaftsverband Erdöl- und Erdgasgewinnung e. V. http://www.erdoel-erdgas.de/content/download/6602/72274/file/Bericht%20Dezember%202014%20Seite%201-3.pdf Accessed 19 October 2016.

Weidema, B. P., C. Bauer, R. Hischier, C. Mutel, T. Nemecek, J. Reinhard, C. O. Vadenbo, and G. Wernet. 2013. The ecoinvent database: Overview and methodology: Data quality guideline for the ecoinvent database version 3. Paper presented at Ecoinvent Report 1(v3). St. Gallen, Switzerland: The ecoinvent Centre.

WI (Wuppertal Institute). 2016. Internal Database. Wuppertal, Germany: Wuppertal Institute for Climate Environment and Energy GmbH.

Wiesen, K. 2010. Ermittlung von Ressourceneffizienzpotenzialen der regenerativen Stromerzeugung durch Windenergie und Biomasse in Deutschland: Erweiterte Fassung. [Calculation of resource efficiency potentials of renewable power generation via wind energy and biomass in Germany. Extended version.] Master's thesis, HAWK Göttingen.

Wiesen, K., J. Teubler, and H. Rohn. 2013. Resource Use of Wind Farms in the German North Sea – The Example of Alpha Ventus and Bard Offshore I. Resources 2(4): pp.504–516.

Wind-projekt (2012): Wind-Wasserstoff System. WIND-projekt Ingenieur- und Projektentwicklungsgesellschaft mbH, Börgerende. http://www.rh2-wka.de/projekt/wind-wasserstoff-system.html?77,14 Accessed 7 January 2016.

Wurzbacher, J. 2014. Capturing CO2 from air. Paper presented at 3rd Conference on CO2 as Chemical Feedstock, 2 December 2014, Essen, Germany.

Xiang, D., S. Yang, X. Liu, Z. Mai, and Y. Qian. 2014. Techno-economic performance of the coal-to-olefins process with CCS. Chemical Engineering Journal 240: pp.45–54.

Zhang, G., Y. Yang, G. Xu, K. Zhang, D. Zhang. 2015. CO2 capture by chemical absorption in coal-fired power plants: Energy-saving mechanism, proposed methods, and performance analysis. International Journal of Greenhouse Gas Control 39: pp.449–462.

Zhao, H., Y. Ge, J. Tan, H. Yin, J. Guo, W. Zhao, and P. Dai. 2011. Effects of different mixing ratios on emissions from passenger cars fueled with methanol/gasoline blends. Journal of Environmental Sciences 23(11): pp.1831–1838.

2.6.3 Reference list for Task 1.3

Bazzanella, A. M., & Ausfelder, F. (2017). Low carbon energy and feedstock for the European chemical industry. Frankfurt am Main

BMWi. (2016). Existenzgründung. Retrieved from http://www.bmwi.de/DE/Themen/Mittelstand/Gruendungen-und-Unternehmensnachfolge/existenzgruendung.html

Brunsting, S., Upham, P., Dütschke, E., Waldhober, M. D. B., Oltra, C., Desbarats, J., Reiner, D. (2011). Communicating CCS: Applying communications theory to public perceptions of carbon capture and storage. International Journal of Greenhouse Gas Control, 5(6), pp.1651–1662.

CEFIC. (2016). Extra-EU chemicals trade balance. The European Chemical Industry: Facts & Figures 2016. Retrieved from http://fr.zone-secure.net/13451/186036/?startPage=13#page=14

Hendriks, C., Noothout, P., Zakkour, P., & Cook, G. (2013). Implications of the Reuse of Captured CO2 for European Climate Action Policies. Retrieved from Utrecht: http://www.scotproject.org/sites/default/files/Carbon%20Count,%20Ecofys%20(2013)%20Implications%20of%20the%20reuse%20of%20captured%20CO2%20-%20report.pdf

Jones, C. R., Olfe-Kräutlein, B., & Kaklamanou, D. (2016). Lay perceptions of carbon dioxide capture and utilisation technologies in the UK and Germany: a qualitative interview study.

Paper Presented at the 14th International Conference on Carbon Dioxide Utilisation (ICCDU), Sheffield, the UK.

Naims, H. (2016). Economics of carbon dioxide capture and utilisation – a supply and demand perspective. Environmental Science and Pollution Research, 1–16. doi:10.1007/s11356-016-6810-2

Olfe-Kräutlein, B., Naims, H., Bruhn, T., & Lorente Lafuente, A. M. (2016). CO2 als Wertstoff – Herausforderungen und Potenziale für die Gesellschaft Potsdam IASS.

Piria, R., Naims, H., & Lorente Lafuente, A. M. (2016). CCU: Klimapolitische Einordnung und innovationspolitische Bewertung. Adelphi Discussion Paper. Retrieved from https://www.adelphi.de/en/publications

Santarius, T. (2012). Der Rebound-Effekt: Über die unerwünschten Folgen der erwünschten Energieeffizienz.

UBA. (2014). Rebound-Effekte. Retrieved from https://www.umweltbundesamt.de/themen/abfall-ressourcen/oekonomische-rechtliche-aspekte-der/rebound-effekte

UN Sustainable Development Knowledge Platform. (2016). Sustainable Development Goals. Retrieved from https://sustainabledevelopment.un.org/sdgs

Wilson, G., Travaly, Y., Brun, T., Knippels, H., Armstrong, K., Styring, P., Bolscher, H. (2015). A VISION for Smart CO2 Transformation in Europe: Using CO2 as a resource.

Zimmermann, A., & Kant, M. (2016). The Business Side of Innovative CO2 Utilisation. Retrieved from http://enco2re.climate-kic.org/wp-content/uploads/2016/01/The-business-side-of-innovative-CO2-utilisation.pdf

Aresta, M., & Dibenedetto, A. (2010). Industrial utilisation of carbon dioxide (CO2). In M. M. Maroto-Valer (Ed.), Developments and innovation in carbon dioxide (CO2) capture and storage technology: Volume 2: Carbon dixide (CO2) storage and utilisation (Vol. 2, pp. 377-410). Great Abington: Woodhead Publishing.

Arning, K., van Heek, J., & Ziefle, M. (2017). Risk perception and acceptance of CDU consumer products in Germany Paper presented at the 13th International Conference on Greenhouse Gas Control technologies, GHGT-3, Lausanne, Switzerland.

Bazzanella, A. M., & Ausfelder, F. (2017). Low carbon energy and feedstock for the European chemical industry. Frankfurt am Main

Bogner, J., Abdelrafie Ahmed, M., Diaz, C., Faaij, A., Gao, Q., Hashimoto, S., Zhang, T. (2007). Waste Management. In B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, & L. A. Meyer (Eds), Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 585–618). Cambridge: Cambridge University Press.

Brandani, S. (2012). Carbon dioxide capture from air: a simple analysis. Energy & Environment, 23(2–3), pp.319–328.

Bruhn, T., Naims, H., & Olfe-Kräutlein, B. (2016). Separating the debate on CO2 utilisation from carbon capture and storage. Environmental Science & Policy, 60, 38–43. doi:http://dx.doi.org/10.1016/j.envsci.2016.03.001

Brunsting, S., Upham, P., Dütschke, E., Waldhober, M. D. B., Oltra, C., Desbarats, J., Reiner, D. (2011). Communicating CCS: Applying communications theory to public perceptions of carbon capture and storage. International Journal of Greenhouse Gas Control, 5(6), 1651–1662.

Capros, P., De Vita, A., Tasios, N., Siskos, P., Kannavou, M., Petropoulos, A., Nakos, C. (2016). EU Reference Scenario 2016-Energy, transport and GHG emissions Trends to 2050. Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/ref2016_report_final-web.pdf

CEFIC. (2016). Extra-EU chemicals trade balance. The European Chemical Industry: Facts & Figures 2016. Retrieved from http://fr.zone-secure.net/13451/186036/?startPage=13#page=14

Chertow, M. R. (2000). Industrial symbiosis: literature and taxonomy. Annual review of energy and the environment, 25(1), pp.313–337.

European Commission. (2011). Energy Roadmap 2050 – Impact Assessment and Scenario Analysis.

European Commission. (2014a). EU ENERGY, TRANSPORT AND GHG EMISSIONS TRENDS TO 2050: REFERENCE SCENARIO 2013.

European Commission. (2014b). A policy framework for climate and energy in the period from 2020 to 2030.

Cremer, C., Esken, A., Fischedick, M., Gruber, E., Idrissova, F., Kuckshinrichs, W., Roser, A. (2008). Sozioökonomische Begleitforschung zur gesellschaftlichen Akzeptanz von Carbon Capture and Storage (CCS) auf nationaler und internationaler Ebene: Endbericht: Wuppertal Institut für Klima, Umwelt, Energie GmbH.

de Coninck, H., & Benson, S. M. (2014). Carbon Dioxide Capture and Storage: Issues and Prospects. Annu. Rev. Env. Resour., 39(1), 243–270. doi:10.1146/annurev-environ-032112-095222

Delft, C. (2017). CCU market options in the Rotterdam Harbour Industrial Complex.

Delgado, A., Lein Kjølberg, K., & Wickson, F. (2011). Public engagement coming of age: From theory to practice in STS encounters with nanotechnology. Public Understanding of Science, 20(6), pp.826–845.

European Commission. (2015). Horizon 2020 Work Programme 2014–2015. General Annexes A–K to the main work programme (full document). Retrieved from http://ec.europa.eu/research/participants/portal/desktop/en/funding/reference_docs.html#doc1.

European Commission. (2016). Clean Energy For All EuropeansCOM(2016) 860. Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/cleanenergy_com_en.pdf

European Commission. (2018, 2018, February 26). Promoting entrepreneurship. Retrieved from https://ec.europa.eu/growth/smes/promoting-entrepreneurship_en

European Parliament. (2011). 2050. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, 12.

Falter, C., Batteiger, V., & Sizmann, A. (2016). Climate Impact and Economic Feasibility of Solar Thermochemical Jet Fuel Production. Environmental Science & Technology, 50(1), 470–477. doi:10.1021/acs.est.5b03515

Hampel, J., & Zwick, M. (2016). Wahrnehmung, Bewertung und die Akzeptabilität von Technik in Deutschland. Technikfolgenabschätzung–Theorie und Praxis, 25. Jg(1).

Hauke, N. (2014). Die grüne Revolution an der Tankstelle? Die Relevanz politischer Narrative am Beispiel der Einführung des Biokraftstoffes E10. In F. Gadinger, S. Jarzebski, & T. Yildiz (Eds), Politische Narrative (pp. 173–197). Wiesbaden Springer.

Hendriks, C., Noothout, P., Zakkour, P., & Cook, G. (2013). Implications of the Reuse of Captured CO2 for European Climate Action Policies. Retrieved from: http://www.scotproject.org/sites/default/files/Carbon%20Count,%20Ecofys%20(2013)%20Implications%20of%20the%20reuse%20of%20captured%20CO2%20-%20report.pdf

IEA. (2014). CO2 emissions from fuel combustion: Highlights. IEA Statistics. Retrieved from https://www.iea.org/publications/freepublications/publication/CO2EmissionsFromFuelCombustionHighlights2014.pdf

Jacobsen, N. B. (2006). Industrial symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects. J. Ind. Ecol., 10(1-2), pp.239–255.

Jilvero, H., Mathisen, A., Eldrup, N.-H., Normann, F., Johnsson, F., Müller, G. I., & Melaaen, M. C. (2014). Techno-economic Analysis of Carbon Capture at an Aluminum Production Plant – Comparison of Post-combustion Capture Using MEA and Ammonia. Energy Procedia, 63, 6590-6601. doi:10.1016/j.egypro.2014.11.695

Jones, C., Kaklamanou, D., Stuttard, W., Radford, R., & Burley, J. (2015). Investigating public perceptions of carbon dioxide utilisation (CDU) technology: a mixed methods study. Faraday Discussions, 183, pp.327–347.

Jones, C. R., Olfe-Kraeutlein, B., Naims, H., & Armstrong, K. (2017). The Social Acceptance of Carbon Dioxide Utilisation: A Review and Research Agenda. Frontiers in Energy Research. doi:doi: 10.3389/fenrg.2017.00011

Jones, C. R., Olfe-Kräutlein, B., & Kaklamanou, D. (2016). Lay perceptions of carbon dioxide capture and utilisation technologies in the UK and Germany: a qualitative interview study. Paper Presented at the 14th International Conference on Carbon Dioxide Utilisation (ICCDU), Sheffield, the UK.

Jones, C. R., Radford, R. L., Armstrong, K., & Styring, P. (2014). What a waste! Assessing public perceptions of Carbon Dioxide Utilisation technology. Journal of CO2 Utilisation, 7, pp.51–54.

Jordal, K., Anantharaman, R., Genrup, M., Aarhaug, T. A., Bakken, J., Lilliestråle, A., Holt, N. J. (2014). Feeding a gas turbine with aluminum plant exhaust for increased CO2 concentration in capture plant. Energy Procedia, 51, 411–420. doi:10.1016/j.egypro.2015.03.055

Jung, J., von der Assen, N., & Bardow, A. (2013). Comparative LCA of multi-product processes with non-common products: a systematic approach applied to chlorine electrolysis technologies. The International Journal of Life-cycle Assessment, 18(4), pp.828–839.

Kant, M. (2017). Overcoming Barriers to Successfully Commercialising Carbon Dioxide Utilisation. Frontiers in Energy Research, 5(22). doi:10.3389/fenrg.2017.00022

Klankermayer, J., & Leitner, W. (2015). Love at second sight for CO2 and H2 in organic synthesis. Science, 350(6261), pp.629–630.

Kurokawa, H., Shirasaki, Y., & Yasuda, I. (2011). Energy-efficient distributed carbon capture in hydrogen production from natural gas. Energy Procedia, 4, pp.674–680. doi:10.1016/j.egypro.2011.01.104

Materialscience, B. (2015). CO2 überzeugt als neuer Baustein für Polyurethane Retrieved from http://presse.covestro.de/news.nsf/id/co2-ueberzeugt-als-neuer-baustein-fuer-polyurethane

Mennicken, L., Janz, A., & Roth, S. (2016). The German R&D Program for CO2 Utilisation – Innovations for a Green Economy. Environmental Science and Pollution Research, pp.1-7. doi:10.1007/s11356-016-6641-1

Metz, B., Davidson, O., De Coninck, H., Loos, M., & Meyer, L. (2005). IPCC special report on carbon dioxide capture and storage. Retrieved from http://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf

Mueller-Langer, F., Tzimas, E., Kaltschmitt, M., & Peteves, S. (2007). Techno-economic assessment of hydrogen production processes for the hydrogen economy for the short and medium term. Int. J. Hydrogen Energ., 32(16), pp.3797–3810. doi:10.1016/j.ijhydene.2007.05.027

Naims, H. (2016). Economics of carbon dioxide capture and utilisation – a supply and demand perspective. Environmental Science and Pollution Research, 1–16. doi:10.1007/s11356-016-6810-2

Naims, H., Olfe-Kräutlein, B., Lorente Lafuente, A. M., & Bruhn, T. (2015). CO2-Recycling – An Option for Policymaking and Society? Retrieved from http://www.iass-potsdam.de/sites/default/files/files/working_paper_co2_recycling-anoption_forpolicymaking_andsociety.pdf doi:10.2312/iass.2016.004

Oles, M., Lüke, W., Kleinschmidt, R., Büker, K., Weddige, H.-J., Schmöle, P., & Achatz, R. (2018). Carbon2Chem® – Ein cross-industrieller Ansatz zur Reduzierung der Treibhausgasemissionen, Carbon2Chem® – A Cross-Industry Approach to Reduce Greenhouse Gas Emissions. Chemie Ingenieur Technik, 90(1–2), pp.169–178. doi:10.1002/cite.201700112

Olfe-Kräutlein, B., Naims, H., Bruhn, T., & Lorente Lafuente, A. M. (2016). CO2 als Wertstoff - Herausforderungen und Potenziale für die Gesellschaft Potsdam IASS.

Olfe-Kräutlein, B., Naims, H., Bruhn, T., Lorente Lafuente, A. M., & Tobias, M. (2014). CO2 as an asset? IASS Fact Sheet, 2/2014. Retrieved from http://www.iass-potsdam.de/sites/default/files/files/fact_sheet_en_2_2014.pdf doi:10.2312/iass.2014.013

Perdan, S., Jones, C. R., & Azapagic, A. (2017). Public awareness and acceptance of carbon capture and utilisation in the UK. Sustainable Production and Consumption, 10, pp.74–84.

Peters, M., Köhler, B., Kuckshinrichs, W., Leitner, W., Markewitz, P., & Müller, T. E. (2011). Chemical Technologies for Exploiting and Recycling Carbon Dioxide into the Value Chain. ChemSusChem, 4(9), pp.1216–1240. doi:10.1002/cssc.201000447

Piria, R., Naims, H., & Lorente Lafuente, A. M. (2016). CCU: Klimapolitische Einordnung und innovationspolitische Bewertung. Adelphi Discussion Paper. Retrieved from https://www.adelphi.de/en/publications

Renn, O. (2005). Technikakzeptanz: Lehren und Rückschlüsse der Akzeptanzforschung für die Bewältigung des technischen Wandels. Technikfolgenabschätzung–Theorie und Praxis, 14(3), pp.29–38.

Santarius, T. (2012). Der Rebound-Effekt: Über die unerwünschten Folgen der erwünschten Energieeffizienz.

Schneider, S. (2017). Der öffentliche Diskurs um die geologische Speicherung von Kohlenstoffdioxid (CCS): Strukturgeographische Differenzierungen und ihre Implikationen für die Medienpräsenz wissenschaftlicher Forschung in deutschen Tageszeitungen am Beispiel von CCS (Vol. 7): LIT Verlag Münster.

Schüwer, D., Arnold, K., Bienge, K., Bringezu, S., Echternacht, L., Esken, A., Viebahn, P. (2015). CO2 ReUse NRW: Evaluating gas sources, demand and utilisation for CO2 and H2 within the North Rhine-Westphalia area with respect to gar qualities

Selma, L., Seigo, O., Dohle, S., & Siegrist, M. (2014). Public perception of carbon capture and storage (CCS): A review. Renewable and Sustainable Energy Reviews, 38, 848–863.

Sternberg, A., & Bardow, A. (2015). Power-to-What? – Environmental assessment of energy storage systems. Energ. Environ. Sci., 8(2), 389–400. doi:10.1039/C4EE03051F

Styring, P., Jansen, D., de Coninck, H., Reith, H., & Armstrong, K. (2011). Carbon Capture and Utilisation in the green economy. Retrieved from http://co2chem.co.uk/wp-content/uploads/2012/06/CCU%20in%20the%20green%20economy%20report.pdf

UBA. (2013). Treibhausgasneutrales Deutschland im Jahr 2050 – Hintergrundpapier.

UBA. (2014). Rebound-Effekte. Retrieved from https://www.umweltbundesamt.de/themen/abfall-ressourcen/oekonomische-rechtliche-aspekte-der/rebound-effekte

UBA. (2016). Power-to-Liquids Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel. Retrieved from: http://www.lbst.de/news/2016_docs/161005_uba_hintergrund_ptl_barrierrefrei.pdf.

van der Veen, E. J., Giannoulas, D., Guglielmi, M., Uunk, T., & Schubert, D. (2013). Disruptive space technologies. International Journal of Space Technology Management and Innovation (IJSTMI), 2(2), pp.24–39.

Van Heek, J., Arning, K., & Ziefle, M. (2017a). Differences between laypersons and experts in perceptions and acceptance of CO2-utilisation for plastic products. Paper presented at the 13th International Conference on Greenhouse Gas COntrol Technologies, GHGT–13, Lausanne, Switzerland.

van Heek, J., Arning, K., & Ziefle, M. (2017b). Reduce, reuse, recycle: Acceptance of CO 2-utilisation for plastic products. Energy policy, 105, pp.53–66.

Varone, A., & Ferrari, M. (2015). Power to liquid and power to gas: An option for the German Energiewende. Renewable and Sustainable Energy Reviews, 45, pp.207–218. doi:http://dx.doi.org/10.1016/j.rser.2015.01.049

von der Assen, N., Jung, J., & Bardow, A. (2013). Life-cycle assessment of carbon dioxide capture and utilisation: avoiding the pitfalls. Energ. Environ. Sci., 6(9), pp.2721–2734. doi:10.1039/c3ee41151f

von der Assen, N., Lorente Lafuente, A. M., Peters, M., & Bardow, A. (2015). Chapter 4 – Environmental Assessment of CO2 Capture and Utilisation. In K. Armstrong, P. Styring, & E. A. Quadrelli (Eds), Carbon Dioxide Utilisation (pp. 45–56). Amsterdam: Elsevier.

von der Assen, N., Müller, L. J., Steingrube, A., Voll, P., & Bardow, A. (2016). Selecting CO2 Sources for CO2 Utilisation by Environmental-Merit-Order Curves. Environmental Science & Technology, 50(3), 1093-1101. doi:10.1021/acs.est.5b03474

Weitze, M.-D., & Weingart, P. (2016). Schlüsselideen, Akteure und Formate der Technikkommunikation. Technikfolgenabschätzung–Theorie und Praxis, 25 Jg (1).

Wilcox, J. (2012). Carbon capture. New York: Springer.

Wilson, G., Travaly, Y., Brun, T., Knippels, H., Armstrong, K., Styring, P., Bolscher, H. (2015). A VISION for Smart CO2 Transformation in Europe: Using CO2 as a resource.

Wüstenhagen, R., Wolsink, M., & Bürer, M. J. (2007). Social acceptance of renewable energy innovation: An introduction to the concept. Energy policy, 35(5), pp.2683–2691.

Zimmermann, A., & Kant, M. (2016). The Business Side of Innovative CO2 Utilisation. Retrieved from http://enco2re.climate-kic.org/wp-content/uploads/2016/01/The-business-side-of-innovative-CO2-utilisation.pdf

3. Task 2: Regulatory Assessment

3.1 Purpose and approach

This chapter first offers a mapping and analysis of the current EU policy framework to determine whether this framework hampers the technologies identified in the shortlist (Task 2.1). Secondly, policy options are logically derived for addressing the issues identified so as to determine if the technologies would benefit from a change in EU policies in order to be deployed at commercial scale (Task 2.2), and thirdly, a preliminary assessment of these options is given (Task 2.3).

Task 2.1
Regulatory analysis and results were derived from a legal analysis of individual policy and legal texts identified as potentially relevant with regards to the needs of CCU technologies, and the impacts they may have on the environment. Given that the EU regulatory framework does not often regulate specific substances such as the CCU products short-listed under Task 1, these specific substances are also not often referred to in the analysis.

Task 2.2
Options for amending the legislation have been developed in response to the identified barriers or gaps. As literature on the topic already exists, many of the options have also been based on policy recommendations from other studies. Furthermore, stakeholder consultation activities have made possible the identifying and refining of the list of options.

Task 2.3
The analysis of impact focused on the likely economic, social and environmental consequences of the implementation of the options. The goal was also to outline some of the further analysis that needs to be made if options appear advantageous, and to outline possible impacts on technologies not studied (e.g. mature CCU technologies, CCS, biofuels, hydrogen).[61] Finally, this Task compared the shortlisted options based on the identified likely impacts and compared the shortlisted options based on their effectiveness and efficiency.

The overall analysis in Task 2 learned from the discussion in Section 2.4 and 2.5 (Tasks 1.2 and 1.3) on environmental impact of short-listed technologies, identified market barriers and the policy context to their development. Stakeholder consultation activities and literature review further makes possible verifying and validating the analysis to ensure that it is comprehensive with regard to the main issues identified by the CCU stakeholder community and previous research.

3.2 Limitations

The analysis in Task 2 has been subject to the following limitations and restrictions:

[61] To the degree possible, we will observe and report on potential impacts for mature technologies not studied as part of the scope in this project and indicate potential further action for the EC. However, due to the time schedule and the size of this project, this testing and reporting will only be preliminary and indicative of potential next steps if the EC finds the proposed policy options worth exploring in further detail. We will agree on a concrete list of technologies with the EC before conducting this exercise a) to account for the unclear meaning of the term 'mature' and b) to use the project's resources efficiently.

- Task 2 is subject to the technical information provided in Task 1. There has been no separate or additional assessment of technical aspects.
- The assessment has been performed without a full understanding of the entire scope of the potential environmental impacts of the shortlisted technologies and CCU technologies in general and is generally limited by the state of current knowledge.
- As mentioned in Section 2 (Task 1) above, many of the CCU technologies are to be classified as being at early development stages, both in relation to the conversion routes and lab-scale application. There are still several stages and years before they are ready for commercialisation, which has made it impossible to '*perform a meaningful quantitative financial and economic analysis of individual CCU products*' (see Section 2.5). This limitation has consequences for the legal assessment as well, as consequences of certain legal instruments or requirements may be challenging to foresee if the commercial criteria for the product are not determined.
- As discussed in Sections 2.4.2 and 2.5.2, economic, commercial and technical data, and local conditions, such as location, availability of renewable energy, CO_2 input source and other raw materials, proximity to water and neighbouring states and markets, etc vary from Member State to Member State. As a result, we concluded in Section 2.6 that certain aspects of the analysis could not be generalised for all projects or identical products. Similarly, the consequences of the framework may differ between Member States and industries, and even projects, routes and value chains for CCU technologies. Although the text may to a large extent give an impression of being generally applicable for the substances, products or routes in question, this is not always the case.
- There is no assessment of intellectual property and related regulations, despite technical know-how and patents being identified as a potential technological advantage in an international setting, as we have not had any indications that IP laws would be any different or more onerous for CCU technologies than other technologies.
- We have not made any assessment of the regulatory framework for state aid, despite the relevance of state aid for technology development for emerging technologies. This is due to several considerations, one of which is the uncertainty regarding the environmental benefits and climate change mitigation potential of the CCU technologies. To address the technologies' eligibility under state aid rules would require a case study of all the shortlisted technologies. The gap in information and lack of scope and extent of the project have made that impossible. However, as the European Commission has decided to perform a review of the Guidelines on State Aid for Environmental Protection and Energy to incorporate fully the general principles laid down in RED II after the entry into force thereof (i.e. RED II), this issue is pending in the EU. No international legal instruments have been analysed.
- No national laws or introduction of EU framework into national frameworks have been analysed in detail, but we have looked into some aspects of the national introduction of the EU framework where it has seemed that national interpretation has led to gaps or differences between frameworks with the potential for stopping development or hindering trade between Member States.
- Time and scope constraints have been reflected in the ability to go into detail, with regard to both identification and development of options and impacts.
- Task 1 has mainly been concerned with the CCU technology, technical route or product, and not so much on how the technology or product may be utilised in the end. The analysis in Task 2 has focused on the aspects identified through Task 1 and from the stakeholder dialogue and workshops. Regulatory hurdles related to the usage or end-user market conditions for all potential products resulting from the CCU routes have only been assessed to some extent.

- This particularly raises the issue of tracing of carbon flows under the Emission Trading System, where an understanding of the fate of the CO_2 contained in products used for different purposes is crucial to properly incentivise carbon capture. There is a wide diversity of possible uses which could therefore not be analysed in great detail in this study.
- The research and inquiries for background material have been limited to publicly available information and literature, or information that was easy to obtain by contacting key stakeholders engaged in or part of the project, including the European Commission.
- As both the production of synthetic fuels and what consequences such production would potentially have on national and EU targets for emissions and energy efficiency require more information and efforts than available to this project at the moment, a further analysis of this has not been performed. Furthermore, an analysis of the climate change mitigation potential and its impact on fulfilment of national and EU targets for emissions reduction by replacing fossil fuels with synthetic fuels is also dependent on more information and efforts than currently available to this project.

3.3 Task 2.1: Analysis of the current regulatory setup

3.3.1 Introduction

Prior to entering a regulatory debate on the status of CCU in the ETS, it is important to remind oneself of some of the key findings and conclusions from Task 1.

The main climate mitigation benefit of CCU processes depends on the net GHG emission balance of the process from cradle-to-gate (during production of the products), irrespective of whether the CO_2 input is from fossil or biogenic origin (e.g. raw biogas), under the provision that conventional products are replaced.[62] Assessments of the climate benefit(s) of CCU processes must be based on a comparison of the CCU production process with the conventional production process, where the following variables influence the overall carbon balance leading to potential 'avoided emissions':

- replacement of conventional (fossil- or bio-based) products (e.g. plastics from oil/gas or biomass) with CO_2-based products;
- sources of CO_2 and their different energy and resource requirements;
- energy sources and their different energy and resource requirements; and
- transport of the CO_2 and CO_2-based products and the different energy and resource requirements thereof.

Considering current use, consumption and disposal patterns, there is no difference in climate effects in the '*storage*' of carbon between CO_2-based and substituted fossil or bio-based ('*conventional*') products. This is because a CCU product always replaces a conventional product identical in chemical composition and physical condition, and both are also used, recycled and disposed of in the same way. A same amount of carbon is therefore contained in a CCU product and in a conventional product for the same amount of time.

Specific uses of mineralisation products can lead to a certain volume of CO_2 being stored almost permanently in the product. Here again it is important to note that CCU mineralisation processes are not proven to store CO_2 in larger quantities or better than the conventional counterpart. Furthermore, storage permanence does not matter in a comparative approach, as

[62] This finding is illustrated in Figure 19: Summary of the effects of CCU to the production, use and end-of-life phase for the conventional and the CO_2-based product life-cycle of Task 1.2 (Section 2.4.4).

again in the case of mineralisation the larger share of the climate benefit come from the carbon intensity of the CCU production process as compared to the conventional process, and it is necessary to compare the net GHG emission balance of the conventional and the CCU mineralisation processes.

However, CO_2 retention and permanent storage matter in GHG emission accounting: where the point of CO_2 capture is and the location of the emission must be taken into account. When this accounting system is the basis of a carbon trade system, such as under the EU ETS, this is even more important for attributing incentives, such as enabling ETS installations to retain emission allowances for avoided emissions. If the carbon is reported as captured in an ETS installation and re-emitted in a non-ETS sector, the emission can go unreported and effectively lead to 'internal carbon leakage'.

CCU contributes to the circular economy. Capturing CO_2 from industrial and waste management processes which would otherwise be released represents the last chance to keep the carbon in the technical-use sphere. It thus supplements the options for reuse and material recycling and can contribute to leaving fossil resources in the ground. CCU based materials, in contrast to CCU fuels, have the further advantage that they can be used several times and feed into material recycling.

Having made these findings, we draw two key conclusions:

- When considering a same product pattern the retention time of carbon in CCU products versus conventional (fossil- or bio-based) products remain the same and thus are irrelevant for measuring the CO_2 balance.
- From a climate mitigation perspective, the benefit of CCU processes depends on the net GHG emission balance the process from cradle-to-gate, for all types of products (minerals, polymers, fuels and chemicals) under the provision that conventional products are replaced.

From a climate mitigation perspective, the benefit of CCU processes depends on the net GHG emission balance of the process from cradle-to-gate, for all types of products (minerals, polymers, fuels and chemicals) under the condition that conventional products are replaced. This understanding of CCU has important consequences and is used as a basis for analysing the policy framework offered by the ETS in Section 3.3.3 and for defining policy options to changing the ETS and MRV in Section 3.4.2 below.

3.3.2 General analysis of the European Union's current regulatory setup

As mentioned above, the regulatory setup that is affecting or may affect CCU technologies and the deployment of those is comprehensive and complex. To set the scene, and provide background understanding to this topic, Task 2.1 begins with a brief summary of the general regulatory setup for CCU in Europe, including current developments.

The policy framework is reviewed with regard to its relevance and implications for CCU and because it constitutes the baseline set of legislation for CCU as of 2018. The analysis aims at identifying both the legislation which poses potential barriers to the development of promising technologies and that which can potentially offer a platform for their incentivisation as part of policy options.

In the next paragraphs a description and a short summary conclusion of the assessment of the different pieces of legislation analysed in this study are presented, organised according to the different thematic policy frameworks they belong to. These policy frameworks were defined based on their common objectives for the purpose of the analysis.

Climate and energy policy framework

The 2030 climate and energy policy sets three targets to be achieved by 2030: a 40% reduction in greenhouse gas (GHG) emission, a 27% increase in the share of renewable energy, and a 27% improvement in energy efficiency relative to 2005 levels and for the economy as a whole.

The GHG emission target is addressed by the Emission Trading System Directive (EC/410/2018, widely known as the ETS Directive) on the one hand, which targets sectors which include power/heat generation and industrial production of products including metals, cement, lime, glass, paper, etc, and the Effort Sharing Decision (406/2009) and the more recent Effort Sharing Regulation (842/2018) on the other hand, which target the transport, construction, agriculture and waste sectors. These targets include a contribution from the sectors covered by the effort sharing legislation of 10% by 2020 and 30% by 2030 (compared to 2005 levels). Furthermore, the contribution from installations covered by the EU ETS is to be 21% by 2020 and 43% by 2030.

The renewable energy target is addressed by the Renewable Energy Directive (2009/28/EC, also known as RED) and its successor, RED II (Directive (EU) 2018/2001.[63] The targeted share of renewable energy consumption in the total energy mix is at least 27% by 2030.[64]

The energy efficiency target is addressed by the Energy Efficiency Directive (2012/27/EU, also known as EED). The energy efficiency improvement target is at least 27%.

These directives have direct relationships to the development of CCU. The high energy needs of CCU technologies may contribute to a delay in meeting the energy efficiency target and may challenge the *'energy efficiency first'* principle.[65] What is more, the potential of CCU technologies for using and increasing the share of renewable energy and their potential for GHG emissions reductions may contribute to hitting the other two targets; however, that depends on the GHG emission performance of the CCU process. As a significant amount of power is needed to transform CO_2 into another material, the use of renewable energy for the purpose of powering CCU processes may actually be rather inefficient compared to alternative uses of that energy, which can be comparatively less carbon-intensive and make a more direct use of renewable electricity, such as e-mobility. However, as pointed out in Task 1,[66] some CCU applications might be considered as energy storage options that could support renewable energy policies as defined in these Directives and can further be considered as options for reductions in emissions from power generation.

Other EU climate and energy-related legislation also relates to these directives. Such being mainly:

- the Monitoring and Reporting Regulation (601/2012, known as the MRR), which provides rules for the monitoring and reporting of greenhouse gas emissions and activity data pursuant to the EU ETS Directive, and the Accreditation and Verification Regulation (Commission Regulation 600/2012, known as the AVR) laying down provisions for the verification of reports submitted pursuant to Directive 2003/87/EC and for the accreditation and supervision of verifiers; together forming the MRV framework of the EU ETS;

[63] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&qid=1546953252892&from=EN

[64] See also Section 2.5.4 of Task 1.

[65] See Proposal for a Directive of the European Parliament and of the Council amending Directive 2012/27/EU on energy efficiency, 2016/0376 (COD), Explanatory Memorandum, p. 3.

[66] See Section 2.5.4, see Barbra Olfe-Kräutlein et al., 2016.

- the Benchmarking Commission Decision (2011/278/EU), which determines transitional Union-wide rules for harmonised free allocation of emission allowances pursuant to Article 10a of the EU ETS Directive;[67]
- the Fuel Quality Directive (2009/30/EC, known as the FQD), which establishes rules to help reduce greenhouse gas and air pollutant emissions from fuels, as well as mechanisms to establish a single fuel market;
- LULUCF Regulation (841/2018), which provides a framework for accounting greenhouse gas emissions and removals related to agricultural land and forestry from 2021 onwards; and
- the Directive on the geological storage of carbon dioxide (2009/31/EC, known as the CCS Directive), which aims to ensure environmentally safe geological storage of CO_2.

The EU climate and energy policy framework regulates all sectors where energy is used and GHG emissions occur. Key to upholding the integrity of this framework is ensuring that a coherent GHG emission accounting system is in place and avoids the risk of double counting. This system is based on the international framework offered by the UNFCCC and guided by IPCC assessments. In particular, emissions which are saved in one sector, for instance industrial emissions, should not be counted again as saved in another sector, such as transport.[68] This issue is discussed in more detail in the following assessment.

<u>Conclusion of this assessment</u>
The climate and energy policy framework constitutes the main body of legislation for incentivising carbon emissions reduction from CCU processes. Overall, CCU processes introduce a logic which differs from the one intended by the different legislative mechanisms. For instance, CCU processes require using a GHG accounting approach which differs from the one required by the existing EU mechanisms, i.e. the tracing of carbon flows under the MRV framework is not entirely feasible in the existing MRR and AVR, due to carbon potentially captured from one sector under the scope of one legislation, such as the metal industry, being regulated under the ETS and when re-emitted in another sector, such as transport, being regulated under effort sharing legislation. The differing scope of such legislation can create a real difficulty in attributing incentives while avoiding double counting of avoided emissions.

<u>Waste and circular economy policy framework</u>

A key issue for EU waste and circular economy policy is the closing of the material loop via the recycling and reuse of waste, overall reducing the amount of waste discarded (whether landfilled or burned) and impacting human health as well as the air, water and soil. This policy framework is composed of the following main policies:

- the EU Action Plan for a Circular Economy (COM(2015) 614 final, known as the CEAP);
- the European Strategy for Plastics in a Circular Economy (COM(2018) 28 final);
- the Waste Framework Directive (2008/98/EC, known as the WFD), which lays down measures to protect the environment and human health related to the handling of waste.

These policies are closely interrelated, as they address the end-of-life issue of products and suggest the approach to considering waste as a new product. The Waste Framework Directive 2008/98/EC (WFD) is of general relevance and particular importance for the CCU mineralisation

[67] The reader should be aware that this is the present legislation affecting EU ETS Phase 3, but there is no consideration of an equivalent legislation that will be required in connection with Phase 4 (as confirmed in Article 10a of the revised EU ETS Directive).

[68] Christensen & Petrenko (2017). CO_2-Based Synthetic Fuel: Assessment of Potential European Capacity and Environmental Performance.

routes without additional mining, since the CaO source is waste products from different industrial processes: slag from steel furnaces, sewage or dust residues from a waste incineration plant. As the analysis will demonstrate, these activities may further be subject to other instruments under the environmental pollution policy framework that, both separately and in combination with the WFD, can pose potential hurdles.

Conclusion of this assessment
This policy framework presents some barriers to the marketing and free movement within the EU market of products containing potentially hazardous substances, due to different national interpretations of the risk involved. Some of these products include products from CCU production processes. The circular economy policy framework offers potential for closing the carbon loop; however, this policy framework currently does not specifically refer to recycling of carbon. Furthermore, materials recycling can, in itself, be a climate-mitigating process, by avoiding the extraction of raw materials and providing an alternative to production processes using these raw materials, which can be more carbon-intensive than recycling.

Products and labelling policy framework

Legislation governing the design, environmental impact and labelling of products is contained in a number of policy tools which are also part of the EU's Sustainable Consumption and Production Policies (EC DG Environment, Sustainable Development). This framework comprises:

- the Construction Products Regulation (305/2011, known as the CPR), which lays down harmonised conditions for the marketing of construction products;
- the Ecodesign Directive (2009/125/EC), which establishes a framework for the setting of ecodesign requirements for energy-related products; and
- the CLP Regulation (1272/2008), which applies to the classification, labelling and packaging of substances and mixtures.

This legislation is closely linked to the waste and circular economy policy framework, as the product policy framework addresses the beginning-of-life of products while the waste legislation addresses end-of-life, therefore together composing a circular approach. Furthermore, these instruments need to be recognised as a co-ordinated part of the EU's aim of replacing hazardous substances with safer substances wherever technically possible. This legislation is therefore relevant to the development of CCU where CCU products still need to be further recognised as part of this body of legislation.

Conclusion of this assessment
Overall, this policy framework has not been identified as posing significant barriers to the development of CCU in general. However, a potential hurdle for certain technologies producing concrete block aggregates has been observed, most likely as a result of flexibilities in the Union policy framework for hazardous substances, resulting in different implementation of, for example, end-of-waste criteria and the use of hazardous substances. This is closely linked to the assessment of the waste and circular economy framework, and, in particular, the WFD. Although the ecolabeling provided for in the framework might potentially have some benefits for CCU technologies in relation to the end users,[69] the current status is that the maturity and characteristics of the CCU technologies as a whole are too unclear and diverse to establish a general effect on CCU.

Environmental pollution policy framework

[69] See Section 2.5.4.

The health and wellbeing of EU citizens is included in the EU's environmental framework. In order to prevent and reduce risks of pollution arising from industrial activities, the EU has created a set of instruments for the regulation and control of emissions into air, water and land.

The main instrument is the Industrial Emissions Directive, which enables integrated prevention and control of pollution arising from industrial activities. Other instruments have been assessed, including the Directive on persistent organic pollutants (POPs), regulating dangerous substances and persistent organic pollutants.

Several of the instruments are relevant for a wide range for industries, and thus many of the CCU routes. For industries involving chemicals, which are many of the CCU routes, the European Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) applies. That regulation imposes responsibilities with regards to the risks concerning chemicals and providing the information on those risks to the industry and has links to several other instruments, such as, for example, the WFD and the CPR.

For the CCU mineralisation routes with additional mineral mining, the Extractive Waste Directive (2006/21/EC) regulates the management of waste for the prevention of pollutions to soil and water from extractive waste materials.

The following list of environmental pollution policy instruments represent the instruments we have examined as part of this analysis:

- the Industrial Emissions Directive (2010/75/EU, known as the IED), which aims to prevent, reduce and as far as possible eliminate pollution arising from industrial activities;
- the Extractive Waste Directive (2006/21/EC, known as the EWD) on the management of waste from extractive industries;
- the Registration, Evaluation, Authorisation and Restriction of Chemicals Regulation (EC 1907/2006, known as the REACH Regulation), which aims to improve the protection of human health and the environment through the better and earlier identification of the intrinsic properties of chemical substances;
- the European Pollutant Release and Transfer Register Regulation (166/2006, known as the E-PRTR Regulation), which provides easily accessible key environmental data from industrial facilities;
- the Persistent Organic Pollutions Regulation (850/2004, known as the POPs Regulation), which aims to protect human health and the environment against the release of POPs;
- the Water Framework Directive (2000/60/EC), which establishes a framework for Community action in the field of water policy;
- the Groundwater Protection Commission Directive (2014/80/EU, known as the GWP Directive) on the protection of groundwater against pollution and deterioration.

Each of the above-mentioned instruments are pieces of the puzzle which is joint co-ordination of pollution prevention and control.

These instruments are all applicable as horizontal regimes for the specific regulations of industrial activities. For instance, the POPs regulation applies in parallel to the REACH regime, still being in force after the introduction of new EU regulations on hazardous substances.

<u>Conclusion of this assessment</u>
Overall, this policy framework has not been identified as posing significant barriers to the development of CCU in general, considering the fact that the regulatory framework should not incentivise production processes which pose risks under this legislation. It is worth noting, however, that the CCU routes are considered not yet eligible as Best Available Techniques

(BAT), as most of them are not yet commercial under the IED, resulting in these technologies currently being unavailable to the Member States as tools to set the emission limit values.

Environmental risk policy framework

In order to prevent and mitigate against environmental damage and accidents, EU risk policy provides instruments for security measures and financial liability. This particularly applies to industries involving dangerous substances, requiring control of major-accident hazards. Important elements include safety reports, emergency plans and information for the public. With regard to financial liability the ELD establishes the '*polluter-pays-principle*'.

- The Seveso III Directive (2012/187EU) relates to the control of major-accident hazards involving dangerous substances.
- The Environmental Liability Directive (2004/35/EC, known as the ELD) relates to environmental liability with regard to the prevention and remedying of environmental damage.

Regarding control of dangerous substances, the Seveso Directive on major accidents is notably part of a wider regime covering the overall prevention and even restriction of certain hazardous substances, see, for example, the text on REACH as part of our analytic regulatory assessment. The applicability of the ELD is connected to the industrial activities included in the IED.

Conclusion of this assessment
Overall, this policy framework has not been identified as posing barriers to the development of CCU. Due to its lower importance, a review of the relevant legislation has been presented in Section 5 (Appendix Task 2).

Environmental impact assessment policy framework

EU legislation requires impact assessments for the evaluation of the environmental implications of plans and projects at a level prior to decision making. Impact assessment is regulated by the following instruments, which have been analysed as part of this study:

- the Strategic Environmental Assessment Directive (2001/42/EU, known as the SEA Directive);
- the Environmental Impact Assessment Directive (2011/92/EU, known as the EIA Directive).

The Directives on environmental assessment (i.e. the SEA Directive and the EIA Directive) aim to provide a high level of protection of the environment and to contribute to the integration of environmental considerations into the preparation of projects, plans and programmes with a view to reducing the environmental impact thereof. The common principle of both of the aforementioned Directives is to ensure that plans, programmes and projects likely to have significant effects on the environment are made subject to environmental assessments, prior to the approval or authorisation thereof. They ensure there is public participation in decision-making and thereby strengthen the quality of decisions.

The obligation to carry out environmental impact assessments for private individual projects can be necessary in order for each Member State to give authorisation and financing. The projects and programmes co-financed by the EU (Cohesion, Agricultural and Fisheries Policies) have to comply with the EIA and SEA Directives in order to receive approval for financial assistance. Therefore these two Directives are crucial tools for sustainable development.

The EIA Directive follows assessments under the SEA Directive. If such assessments arise simultaneously under both Directives, *'Member States should be able to provide for co-ordinated and/or joint procedures fulfilling the requirements'*.[70]

The SEA Directive establishes rules for the contribution of the integration of environmental considerations into the preparation and adoption of plans and programmes by ensuring that, in accordance with this Directive, environmental assessments are carried out for certain plans and programmes which are likely to have significant effects on the environment.

<u>Conclusion of this assessment</u>
Overall, this policy framework has not been identified as posing barriers to the development of CCU. Due to its lower importance, a review of the relevant legislation has been presented in Section 5 (Appendix Task 2).

<u>Financing programmes and instruments</u>

There are also a number of EU financing programmes and instruments which could, or already do, finance CCU projects (as discussed in Section 2.3.4 of Task 1).

- Horizon 2020 – the Framework Programme for Research and Innovation;
- the Research for Coal and Steel Fund (the RCSF);
- the LIFE Climate Action sub-programme;
- the European Fund for Strategic Investments (the EFSI);
- the European Structural and Investment Funds (ESI Funds), composed of the European Regional Development Funds (ERDF) and Cohesion Funds (CF).

<u>Conclusion of this assessment</u>
The resources of the EU's financing programmes and instruments have to date been mainly targeted at research and development projects for fuels, and less so at the scaling-up of technologies, due to their known low TRL. Other technologies involving the production of minerals, chemicals and polymers have received less support.

In the following Sections, we cover in detail the contents and purpose of key legal and regulatory instruments and their relevance to CCU.

3.3.3 The Emission Trading System Directive (EC/410/2018)

In operation since 2005, the EU ETS is a key instrument for achieving the European Union's ambition of reducing its emissions of greenhouse gasses and complying with the international agreements made under the UNFCCC (United Nations Framework Convention on Climate Change). More than 11,000 installations in the EU and partner countries are regulated by the EU ETS and committed towards an EU-wide reduction target set out as an annual linear reduction factor applied to total emissions. By making possible trading in emission allowances the system is designed to achieve such reductions at the lowest possible costs.

The EU ETS is set forth in several Directives, Regulations, Guidelines and legal cases. The figure below provides an overview.

[70] See Recital 3 of Directive 2014/52/EU.

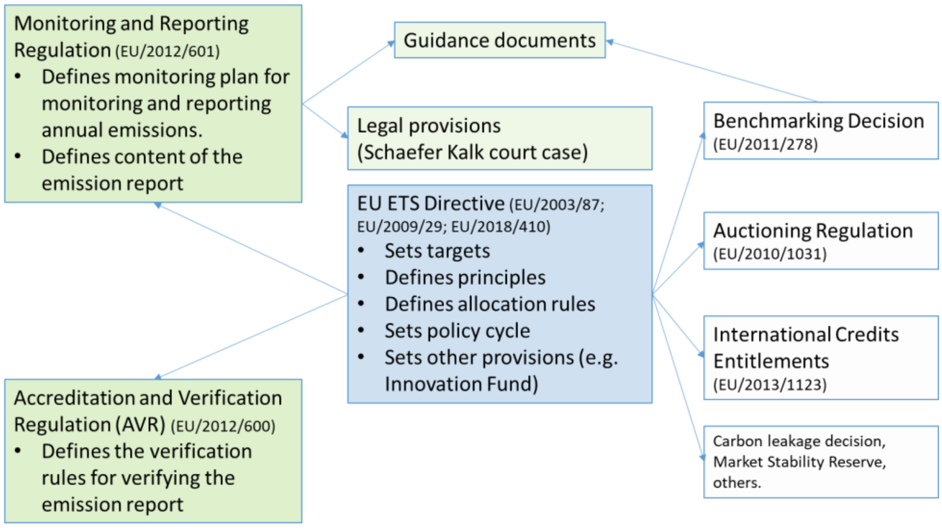


Figure 50: Overview of the key legislative acts that compose the EU ETS (own work)

The most important aspects for CCU are the blue- and green-shaded areas in Figure 50. In the following paragraphs we will look at the EU ETS Directive itself. First, we present the current role of CCU techniques in the present Phase 3 of the EU ETS (until the end of 2020). Next we discuss the CJEU's preliminary judgement regarding the *Schaefer Kalk* case, and then look at the ETS in Phase 4 (2021–2030). In paragraph 3.4.3 we assess the regulations relating to Monitoring and Reporting (MRR) and Accreditation and Verification (AVR).

CCU in the current Phase 3 of the EU ETS

The EU ETS Directive sets out the motivation behind, scope and general outline of the ETS; the implementing details are regulated through various regulations and guidelines that refer to the EU ETS Directive. In the present legislation transfer of CO_2 is only eligible for emission reduction under very specific conditions (in order to close potential loopholes). Those conditions are set out in the Monitoring and Reporting Regulation (EC/601/2012, the MMR) and state that the transfer of carbon contained in products should only be to other EU-ETS installations and the transfer of pure CO_2 should only occur for the purposes of storage in a geological storage site pursuant to the Union's greenhouse gas emission allowance trading system, which is at present the only form of permanent storage of CO_2 accepted under the Union's greenhouse gas Emission Trading System. In Recital 13 of the MRR Regulation (EC 601/2012) it is stated that 'those conditions should not, nevertheless, exclude the possibility of future innovations.'

The EU ETS legislation in place for Phase 3 thus does not explicitly acknowledge CCU as a means for reducing CO_2 emissions. In cases where carbon is captured in a product, such as in the production of urea, the MRR (and Guidance documents) have emphasised that these emissions should be accounted for under the EU ETS as an emission when urea is used as a fertiliser and the contained carbon is released (see Annex IV of the MRR (EC/601/2012)). The inclusion of the CO_2 temporarily contained in a product has been made 'to close potential loopholes'.

The fact that the current EU ETS legislation does not recognise CCU as a means for reducing CO_2 emissions also implies that CCU is not included in the calculation of the benchmarks. Community-wide ex-ante benchmarks are being used in the EU ETS to determine the amount of free allowances for companies active in sectors prone to carbon leakage. In most cases, the relevant benchmark is calculated for typical products and the relevant benchmark level has been set at the average performance of the most efficient 10% of installations in the given sector or subsector in the EC for the years 2007–2008.

Preliminary ruling regarding precipitated calcium carbonate (the *Schaefer Kalk* case)

This situation has been altered to some extent through the judgement of the European Court of Justice (the CJEU) and the opinion of the advocate general expressed in January 2017 regarding the case of *Schaefer Kalk GmbH & Co. KG v Bundesrepublik Deutschland*, after a request for a preliminary ruling on the issue of transfers of CO_2 used in the production of precipitated calcium carbonate by Schaefer Kalk was made by the Verwaltungsgericht Berlin in 2015.[71] This judgement and its implications have been described below in further detail.

In 2012 a German lime-producing company named Schaefer Kalk asked the German authorities[72] if the CO_2 transferred from an installation inside the EU ETS to an installation outside the EU ETS, where it was used in the production of Precipitated Calcium Carbonate (PCC), could be exempted from being reported under its monitoring plan, as that CO_2 was not emitted into the atmosphere but 'chemically bound' in the product.[73] During Phase 2 of the EU ETS (2008–2012) the CO_2 used in the production of PCC was, in most countries, not regarded as CO_2 emissions for which allowances had to be surrendered. However, in Phase 3 of the ETS harmonised rules for reporting emissions were established in the MRR (EC/601/2012) which specified that CO_2 taken up in products such as precipitated calcium carbonate products should, in general, be regarded as emissions. Article 49 of the MRR (EC/601/2012) states that flows of carbon can only be deducted from the reported emissions '*for the purpose of transport and long-term geological storage as permitted under Directive 2009/31/EC*' (i.e. the CCS Directive, see para. 3.4.1). The last sentence of Article 49 further states that '*For any other transfer of CO_2 out of an installation no subtraction of CO_2 from the installation's emissions shall be allowed*.' In Section 10 of Annex IV to the MRR (EC/601/2012) it is further specified that '*Where CO_2 is used in the plant or transferred to another plant for the production of PCC (precipitated calcium carbonate), that amount of CO_2 shall be considered emitted by the installation producing the CO_2*.'

In its judgement dated 19 January 2017 the CJEU argued that the MRR's emissions definition requirements exceed the intentions of the ETS Directive, which are, according to Article 3(b) of Directive 2003/87, defined as 'the release of greenhouse gases into the atmosphere from sources in an installation'. In this case the court ruled that CO_2 which is chemically bound in a stable product should not be regarded as emission into the atmosphere. Therefore the CJEU concluded that CO_2 transferred to another installation for the production of PCC in the case of the process used by Schaefer Kalk should not be counted as CO_2 emissions.

This preliminary ruling and the argument that CO_2 could be chemically bound in a product have been useful in acknowledging that some carbon capture and utilisation processes should be recognised under the ETS as not leading to emissions into the atmosphere. However, the ruling raises significant challenges with regard to its implementation.

First of all, the term 'chemically bound' should not be mistaken for 'permanently bound', as many products can chemically bind carbon, while CO_2 can still be released depending on the product use. For instance, PCC is used in, among other applications, paper manufacturing and the production of plastics and pharmaceuticals, as well as in a range of high-quality mortar and plaster products for the construction trade. See the box below for a more detailed description of PCC applications and the implications for carbon accounting. This raises a critical issue with

[71] Judgment of the Court (First Chamber) dated 19 January 2017 – Schaefer Kalk GmbH & Co. KG v Bundesrepublik Deutschland. Request for a preliminary ruling from the Verwaltungsgericht Berlin. Case C-460/15. Retrieved from: http://curia.europa.eu/juris/liste.jsf?language=en&num=C-460/15#

[72] The Deutsche Emissionshandelsstelle im Umweltbundesamt (German Emissions Trading Authority at the Federal Environment Agency, the DEHSt).

[73] PCC is a material that is widely used, especially in the paper industry, as a coating and filling material.

regard to the integrity of the ETS as a policy instrument for climate mitigation: if the CO_2 bound in PCC used in a final product (paper, plaster, etc) is emitted in a sector not covered by the ETS, this CO_2 may not be accounted by any installation and therefore 'escape' the ETS, leading to what can be termed 'internal carbon leakage'.

Box 2: Applications for precipitated calcium carbonate (PCC) and resulting CO_2 emissions

Precipitated calcium carbonate (PCC) is a filler used in many applications, such as paper, plastics, rubbers, paints, drugs and so on. Its high purity, well-ordered particle size and morphology make it the white filler of choice (Jimoh et al., 2017). Today PCC is the most widely used mineral in paper-making, as a filler and a coating pigment to help produce papers with excellent whiteness and gloss, and enhance the printing properties of paper.

In plastics PCC is by far the most important mineral for compounding with polymers. By weight it accounts for more than 60% of the filler and reinforcements market and is used in various polymers, rubbers and sealants. For instance, breathable PE-films used for, inter alia, producing disposable sanitary products (such as baby diapers) are made using PCC.

PCC also finds uses in:

- coatings, where it results in opacity and increased weather resistance;
- flue gas desulphurisation, to remove emissions and waste water treatment;
- fertiliser use in agriculture, ensuring calcium supply and stable ph in soils;
- filler material in concrete applications such as wares, ready-mixes and prefabricated elements;
- other applications (such as glass, the ceramics industry, dental care and cosmetic products).

While the CO_2 in PCC is chemically bound in the product and does not result in emissions during product use, end-of-life treatment may or may not result in emissions. For instance, incineration of carbon-based products will result in emissions, in contrast to recycling, or even landfilling, (aside from energy use), which can lead to multiple reuse of the carbon or even permanent storage. In summary, the current economic model allows a variety of end-of-life treatments which cannot reasonably be predicted or monitored under the current EU carbon accounting systems.

Secondly, recognising the abovementioned risk of internal carbon leakage, the court put forward as an argument in paragraph 43 of the judgement that

> it does not appear, in the first place, that the guarantees taken as a whole arising, on the one hand, from the monitoring and reporting scheme provided for in Directive 2003/87 and from the provisions of Regulation 601/2012 other than those at issue in the main proceedings, and arising, on the other, from the powers of review and verification conferred on the competent authorities of the Member States […] would not be sufficient to avoid the risk of circumventing the emissions allowance scheme upon the transfer of greenhouse gases to an installation, such as that where the PCC is produced, not subject to that scheme.

In sum, this argument suggests that the review and verification powers of the competent authorities in Member States would enable them to verify whether a CCU product stays within the scope of the ETS. This argument has been contested, due to limitations in powers of entry and the affordability of conducting inspections of installations receiving CCU products and possibly outside of the ETS, affecting competent authorities as well as EU ETS verifiers with regard to their ability to carry out sufficient checks.[74]

Thirdly, the CJEU took an installation-centric approach, meaning that the judgement was made looking at the PCC product produced using Schaefer Kalk's process following an understanding of its chemical properties. However, this approach may hardly be observed in PCC production in other installations or with regard to other products, and in particular should not lead to the blind application of exemptions on surrendering allowances per type of product. The ETS regulates installations and their emissions, whereby it considers the industrial process(es) within an installation and which leads to emission of CO_2 (due to industrial production or processing). It would not be possible to regulate a type of product (such as PCC) based on a general understanding of its carbon balance throughout its life-cycle. The preliminary ruling has therefore not allowed a clear-cut definition of which other processes could be incentivised under the ETS (i.e. exempt from surrendering allowances).

In summary, while the preliminary ruling of the CJEU has allowed Schaefer Kalk to be exempt from surrendering allowances due to its capture and transfer of CO_2, the transfer of chemically bound carbon within PCC may lead to CO_2 being re-emitted outside of the boundaries of the ETS. This would lead to internal carbon leakage, where CO_2 emissions down the product chain are not reported. In practice, this risk is difficult to mitigate using existing monitoring and verification measures. The ruling should not be applied to other products without an assessment of the given CCU process in order to understand how the CCU product is made and what it may be used for to avoid internal carbon leakage. A review of options for addressing the judgement can be found in Section 3.4.2.

The use of CCU in the revised ETS Framework after 2021

The revised ETS Directive (EC/410/2018) was adopted in 2018. In the revised text the European Parliament voted to include CCU in Recital 14, defining the EU ETS support for innovative technologies:

> The main long-term incentive arising from Directive 2003/87/EC for the capture and storage of CO_2 ('CCS'), for new renewable energy technologies and for breakthrough innovation in low-carbon technologies and processes**,** including environmentally safe carbon capture and utilisation ('CCU'), is the carbon price signal it creates and the fact that allowances will not need to be surrendered for CO_2 emissions which are avoided or permanently stored. In addition, in order to supplement the resources already being used to accelerate demonstration of commercial CCS facilities and innovative renewable energy technologies, allowances should be used to provide guaranteed rewards for deployment of CCS or CCU facilities, new renewable energy technologies and industrial innovation in low-carbon technologies and processes in the Union for CO_2 stored or avoided on a sufficient scale, provided an agreement on knowledge sharing is in place.

The purpose of preambles such as Recital 14 is to identify and explain the reasons for the provision in the operative part of the given Directive. Therefore the specific articles must be interpreted in light of the preamble recitals and in the revised Directive, CCU may have two potential roles:

- as a carbon reduction measure, when carbon emissions are *avoided or permanently stored*;
- as a technique eligible for support through the newly established Innovation Fund.

[74] In Section 3.4.2.4 we have reviewed in further detail options for such verifications and other methods for tracing CCU products along a product-chain for the purpose of ensuring that they remain within the boundaries of the ETS.

In response to the above-cited revision of the EU ETS Directive proposed by the Parliament the European Commission stated in the interinstitutional file COM(2015)0337 – C8-0190/2015 – 2015/0148(COD)[75] that CCU techniques would only be included at the time of a review of the ETS Directive:

> The Commission takes note of the European Parliament's proposal to exempt emissions verified as captured and used ensuring a permanent bound from surrender obligations under the EU ETS. Such technologies are currently insufficiently mature for a decision on their future regulatory treatment. In view of the technological potential of CO_2 Carbon Capture and Use (CCU) technologies, the Commission undertakes to consider their regulatory treatment in the course of the next trading period, with a view to considering whether any changes to the regulatory treatment are appropriate by the time of any future review of the Directive. In this regard, the Commission will give due consideration to the potential of such technologies to contribute to substantial emissions reductions while not compromising the environmental integrity of the EU ETS.

These effects are described in Box 3 below.

Box 3: Considerations with regard to including CCU in the ETS on the harmonised allocation rules and for meeting the 2030 carbon targets

Considerations in terms of free allocation

Currently some allowances are distributed for free according to EU-wide harmonised rules as outlined in what are known as the 'Benchmarking Decisions' (2011/278/EU) ensuring that the same rules apply to installations of the same type across all Member States. The allocation of free allowances is capped by 'product benchmarks' to strengthen the incentives for the reduction of greenhouse gas emissions and to reward the most efficient installations. These benchmarks are set at the most efficient 10% of installations, implying that no installation in the EU ETS receives a higher amount of emissions per unit of historic output than the most efficient 10% of installations do.

These benchmark values are currently being updated. Recital 8 of the ETS Directive (EC/2018/410) states that 'the benchmark values for free allocation applicable from 2013 onwards should be reviewed in order to avoid windfall profits and to reflect technological progress in the sectors concerned.' The revision of the rate of technological progress that is to be applied in the benchmarks is defined in two periods. For the period 2021–2025 the rate of technological progress is to be determined on the basis of the information submitted pursuant to Article 11 of the EU ETS for 2016 and 2017. By way of a comparison of that data with the benchmark values contained in the Benchmarking Decision the EC will determine the annual reduction rate for each benchmark and apply it to the benchmark values applicable in the period from 2013 to 2020 with respect to each year between 2008 and 2023 to determine the benchmark values for the period from 2021 to 2025. For 2026–2030 the European Commission will determine the rate of progress on the basis of the information supplied in 2021 and 2022.

If CCU were to be recognised within the framework of the EU ETS as a means for lowering verified CO_2 emissions, that would be reflected in the verified rate of technological progress which is to be placed on each benchmark value.

Considerations in the relative effort of the EU ETS towards meeting the 2030 carbon

[75] Retrieved from: http://www.emeeting.europarl.europa.eu/committees/agenda/201711/ENVI/ENVI(2017)1127_1/sitt-6973473

target

The EU ETS delivers on the 2030 climate ambition of the EU that sets the target of at least a 40% reduction in GHG emissions compared to 1990. This ambition was committed to through the Nationally Determined Contribution (NDC) under the UNFCC. The target is divided between an EU ETS element and a non-ETS element. Within the EU ETS the ambition is to lower emissions by 43% compared to 2005 by way of the EU ETS Directive (EC/2018/410). For the non-ETS element the ambition is to lower emissions by 30% compared to 2030 by way of the Effort Sharing Regulation (EC/2018/842, the ESR). The ESR sets a national cap on GHG emissions from non-ETS sectors for each Member State. The idea of a higher ambition in the ETS is reflected in the agreement that the ETS sectors can reduce emissions at lower costs than the non-ETS sectors, and the consideration that various other policy efforts (e.g. the Renewable Energy Directive) also affect the ETS cap. Therefore the division reflects cost-minimisation considerations.

The ESR's greenhouse gas emissions reduction targets for 2030 are to be determined in relation to the level of each Member State's 2005 reviewed greenhouse gas emissions covered by the ESR. The inclusion of CCU in the EU ETS risks affecting the EU ETS target, by opening the system to CO_2 transfers from inside the EU ETS to non-ETS sectors. Such emissions would then fall under the ESR, which has a less ambitious cap and different MRVA requirements. Thus the total emissions of the EU may increase and the overall 40% reduction target in 2030 may be compromised. The Schaefer Kalk case, for example, implied a shift of emissions within the ETS to a product that is produced outside the ETS. When this is counted as CO_2 reduction within the EU ETS the increase of CO_2 emissions through incineration of paper waste at a later stage should be accommodated in the non-ETS element through additional efforts as part of Effort Sharing. Therefore recognising CCU as a carbon reduction technique within the EU ETS may have consequences for the Effort Sharing Regulation or compromise the overall GHG target of the EU.

In this study we have provided additional clarity regarding the carbon reduction potential of CCU technologies and proposed options with regard to including CCU under the ETS in a future review process, while preserving its environmental integrity. Below is therefore provided an interpretation of the concepts of 'avoided emissions' and permanent CO_2 storage in the context of CCU technologies offering this.

The two potential roles for CCU as a carbon reduction measure and as a technique eligible for funding from the Innovation Fund have been assessed below in more detail.

<u>CCU as a carbon reduction measure</u>

Recital 14 states that it is possible for CCU to be recognised as '*a breakthrough innovation in low-carbon technologies and processes*' where '*allowances will not need to be surrendered for CO_2 emissions which are avoided or permanently stored'.* 'Avoided emissions' is thus introduced as a new concept that needs to be operationalised in the context of the EU ETS. The other mention to CCU in the ETS Directive relates to its inclusion as a technique eligible for funding under the Innovation Fund, with Article 10a(8) setting the requirement for CCU projects to deliver net reduction in emissions and ensure avoidance or permanent storage of CO_2.

A broad understanding of the concept of 'avoided emissions' could entail the understanding proposed in Section 3.3.1 above, where emissions are avoided when considering the replacement of a conventional production process with a CCU process. However, this approach cannot be implemented in the context of the functioning of the ETS, which has within its scope installations and their emissions and can assume neither upstream CO_2 savings nor the comparative approach presented in Task 1.2, where a fossil- or bio-based carbon feedstock is replaced with recycled carbon in a CCU production process. **This means that CO_2 avoided as a result of the replacement of a conventional process and fossil- or bio-based carbon feedstock can neither be used to justify emissions avoided nor to justify exemptions from having to surrender EU allowances. We have identified this as a problem for the proper incentivisation of CCU processes, taking into account their actual climate mitigation potential, which does not occur within the boundaries of a single installation.**

The other form of carbon capture which the ETS currently can incentivise is where the carbon is permanently stored, such as in the case of carbon capture and geological storage.[76] For the regulator this provides flexibility to classify CCU technologies that result in permanent storage as eligible under the ETS Directive and subject to exemption. However, and as can be concluded from Task 1.2 (see also Section 3.3.1), storage permanence and longer retention time do not, on their own, promise that a net climate benefit will be delivered by the CCU product compared to a conventional product which has the same properties and uses, unlike in the case of CCS, where, at least in the EU, the only incentive to use CCS is to avoid GHG emissions into the atmosphere.

Furthermore, the climate mitigation potential of certain CCU processes is still unclear even where it is thought to be potentially stored permanently. As exemplified in the case of the production of serpentine in Section 2.4.4 (Task 1) of this report, not all emitted CO_2 is taken up by the reactive material, and the amount of CO_2 that is captured in the product is subject to variation and is difficult to estimate. As a second example, concrete is known to take up carbon during its life-time, contributing to strengthening of the material. This process can be accelerated by using recycled CO_2 in a process called concrete curing; however, there is not enough scientific knowledge about the extent to which concrete curing makes possible higher absorption of CO_2 than would normally occur, and therefore that the curing process has an added value over the normal carbonation process. Overall this means that, unless a mineralisation process is proven to store carbon better or for a longer period of time than a conventional process, CCU should not be incentivised solely on the basis of storage permanence.[77]

As a conclusion to these observations, and recalling the premises put forward in Section 3.3.1, we have derived the following possible approaches to processes where CO_2 is temporarily retained and those where it is permanently stored:

- CCU processes where the CO_2 is not permanently stored (i.e. where the CO_2 is likely to be re-emitted at any timescale shorter than an almost 'permanent' duration of at least a thousand years, as understood by the IPCC) should not be rewarded under the ETS for saving *any* or all of the volume of CO_2 contained in the product. They can instead be incentivised on the basis of the *net* volume of CO_2 avoided.
- CCU processes where the CO_2 can potentially be stored permanently can be incentivised on the basis of the net volume of CO_2 avoided and stored. Should permanent storage still be selected as a criterion for incentivisation, mechanisms should ensure that the use of the product ensures permanent storage; a difficult process which raises feasibility and cost issues, as mentioned above.

These understandings form the basis of options proposed in Section 3.4.2 further below.

[76] As suggested by the IPCC UNEP Special report on *Carbon dioxide capture and storage*, geological storage can lead to storage of the CO_2 for over a thousand years.

[77] An issue of a different nature is that if the product is saturated with CO_2 from exhaust gasses, other potentially toxic trace elements can be captured in the product as well. Depending on the use and disposal of these toxic material, that could violate the qualification 'environmentally safe CCU' encapsulated in Recital 14 of the EU ETS Directive.

<u>*CCU as a technique eligible for funding from the Innovation Fund*</u>

The Innovation Fund is described in Article 10a paragraph 8 of the revised ETS Directive (see also Box 4). Among CCS and low-carbon products, CCU is also recognised as a technique eligible for funding. Article 10a paragraph 8 sets two important qualifications for CCU projects to be eligible for funding: (1) '*contribute substantially to mitigating climate change*'; and (2) '*Projects involving CCU shall deliver a net reduction in emissions and ensure avoidance or permanent storage of CO_2*'.

This implies that a CCU project should evidence a net reduction in emissions. Task 1.1 has evaluated this claim and concluded that a standardised life-cycle assessment for CCU products and minimum GHG savings and minimum resource efficiency requirements compared to conventional technologies would be a necessary precondition for **possible eligibility under a future ETS innovation fund** and needs to be undertaken for each application individually.

Box 4: Innovation Fund in the EU ETS 2021–2030

The main aim of the Innovation Fund is to stimulate development of low carbon technologies which '*shall not yet be commercially available but shall represent breakthrough solutions or be sufficiently mature to be ready for demonstration at pre-commercial scale*'. While carbon pricing, such as in the EU ETS, can help with regard to deploying low carbon technologies, the relationship between deployment and development cannot be properly addressed by a carbon price alone. Therefore development of technologies can be enhanced by directed subsidy programs, such as those provided in the Innovation Fund.

The proposed Innovation Fund will be one of the largest funds in the world to support low carbon technology developments: 400 million allowances will be reserved from 2021 onwards for this purpose, of which 325 million will come from the amount of free allowances and 75 million from the amount of auctioned allowances. In addition, a further 50 million of unallocated allowances from 2013–2020 that otherwise go into MSR will be added, together with, as early as 2019, any possible un-used or remaining funds from the NER 300 Programme. In theory, a further 50 million allowances could be added to the fund post 2025, if these are not used for free allocation to industry. With the predicted average allowance prices ranging between €18 and €31 (Bloomberg, 2018),[78] the fund could thus easily reach the €8 billion to €15 billion available for funding of low carbon technologies. The fund will thus be much larger than its predecessor, the NER 300 programme.

3.3.4 The Monitoring and Reporting Regulation (Commission Regulation (EU) 601/2012) and the Accreditation and Verification Regulation (Commission Regulation (EU) 600/2012)

The rules related to the compliance cycle are set out in the Monitoring and Reporting Regulation (Commission Regulation 601/2012, the MMR) and the Accreditation and Verification Regulation (Commission Regulation 600/2012, the AVR). Below is an assessment of both those regulations, as they are crucial for the deployment potential of CCU activities under the EU ETS.

The MRR provides rules for the monitoring and reporting of greenhouse gas emissions and activity data pursuant to the EU ETS Directive and is relevant for CCU activities as long as the activities are covered by the EU ETS Directive. Installations and aircraft operators covered by the EU ETS are required to have an approved monitoring plan for monitoring and reporting annual emissions, as part of their permit to operate. Each year each operator must submit an

[78] Bloomberg, 2018. Pollution Market Gets a Boost in EU With Move to Reduce Glut. Article 26 February 2018. https://www.bloomberg.com/news/articles/2018-02-26/pollution-market-gets-a-boost-in-eu-with-move-to-reduce-glut

emissions report. The data for a given year must be verified by an accredited verifier by 31 March of the following year.

The current MRR from the EC does not recognise CCU as a carbon abatement technique eligible for a reduction of CO_2 emissions to be reported under the EU ETS. Provisions have been made for CCS only under Article 49 ('Transferred CO_2') of the MRR.[79] That article states that transferred CO_2 should not count as emissions under the EU ETS only if it is transferred for the purposes of storage in a geological storage site pursuant to the Union's greenhouse gas emission allowance trading system, which is at present the only form of permanent storage of CO_2 accepted under the EU ETS.

Article 49 states explicitly that 'For any other transfer of CO_2 out of the installation, no subtraction of CO_2 from the installation's emissions shall be allowed'. As we have seen above, in the *Schaefer Kalk* case the CJEU has concluded that this Article is not in line with the definition of emissions in the ETS Directive. Therefore this Article will need to be adapted in future update of the MRR, or CCU should be regulated through another provision. This has been discussed in the following Section, where policy options are introduced.

In addition to the MRR, the AVR lays down provisions for the verification of reports submitted pursuant to Directive 2003/87/EC and for the accreditation and supervision of verifiers. In Article 17, paragraph 3, the Regulation states that in the case of transfer of CO_2, both the transferring and receiving installation shall be checked by the verify authority with regard to whether:

> differences between the measured values at both installations can be explained by the uncertainty of the measurement systems and whether the correct arithmetic average of the measured values has been used in the emission reports of both installations. Where the differences between the measured values at both installations cannot be explained by the uncertainty of the measurement systems, the verifier shall check whether adjustments were made to align the differences between the measured values, whether those adjustments were conservative and whether the competent authority has granted approval for those adjustments.

3.3.5 Directive 2012/27/EU on Energy Efficiency (the Energy Efficiency Directive, EED)[80]

On 25 October 2012 the EU adopted Directive 2012/27/EU on energy efficiency. The Energy Efficiency Directive (the EED) aims to meet the 20% target for energy efficiency in 2020, and improvements beyond 2020. Furthermore, '[i]t lays down rules designed to remove barriers in the energy market and overcome market failures that impede efficiency in the supply and use of energy and provides for the establishment of indicative national energy efficiency targets for 2020.'[81]

The EED is part of the EU climate and energy policy framework and an important instrument for the Energy Union, having 'energy efficiency first' as a key element.[82] The EED is closely tied to the ETS Directive and the Effort Sharing Decision (the ESD) and the new Effort Sharing Regulation (the ESR). When implementing the 20% energy efficiency target (i.e. aiming to save

[79] Commission Regulation (EC/601/2012).

[80] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC (Text with EEA relevance).

[81] Article 1, paragraph 2 of Directive 2012/27/EU.

[82] See Proposal for a Directive of the European Parliament and of the Council amending Directive 2012/27/EU on energy efficiency (Text with EEA relevance) – COM(2016) 761 Final, Explanatory Memorandum, page 2.

20% of the Union's primary energy consumption by 2020 compared to projections), the EC had to monitor the impact of new measures on the ETS Directive in order to maintain the incentives in the emissions trading system rewarding low carbon investments and preparing the ETS sectors for the innovations needed in the future, taking into specific consideration the industries that are subject to a significant risk of carbon leakage.[83] Following the Conclusions of the European Council of 17 June 2010 under the process of the Union's 'Europe 2020 Strategy' confirming that this target must be achieved, in order to implement this objective at national level, Member States are required to set national targets in close dialogue with the Commission and to indicate, in their National Reform Programmes, how they intend to achieve those targets, see Article 3, paragraph 1 of the EED.[84] Providing a set of minimum requirements, the EED permits the Member States to impose more stringent measures than those provided in the provisions of the EED, see Article 1(2) of the EED. The EC has, however, provided tools to help officials in Member States implement the EED and thus secure a certain level of harmonisation between the Member States.

The Member States are subject to national energy efficiency targets pursuant to certain principles and minimum requirements and considerations,[85] implying that the direct impact on the shortlisted technologies might first and foremost be visible when examining national policies and framework subject to the EED. When establishing indicative targets the Member States have to take into account 'development of all sources of renewable energies, nuclear energy, carbon capture and storage'.[86] Furthermore, the EED recognises that 'Member States should be able to take into account national circumstances affecting primary energy consumption, such as remaining cost-effective energy-saving potential, changes in energy imports and exports, development of all sources of renewable energies, nuclear energy, carbon capture and storage, and early action' when setting indicative national energy efficiency targets,[87] implying that each Member State should take a holistic approach when setting its targets. CCU has not been included as a separate consideration in the EED. That does not imply that the effects on energy production and consumption resulting from the CCU routes are excluded from consideration, see the wording 'such as'. CCU technologies potentially need to be taken into consideration when setting the targets, both from the limiting and enabling points of view. As observed in Task 1, several of the CCU routes are energy intensive, implying that deployment of such technologies would potentially affect primary energy consumption and development of renewable energy sources. Subject to the EED, it is legitimate for the Member States to restrict the deployment of such technologies to meet the targets. However, given the potential for energy storage in, for example, synthetic fuels, certain CCU technologies may also be viewed advantageous under the targets.

Energy efficiency targets are linked to the ESD and the ESR. Energy efficiency measures are a cost-effective way of helping Member States achieve the ETS and ESD/ESR targets. Article 7 of the Directive requires Member States to achieve actual energy savings through an energy efficiency obligation scheme and therefore encourages energy efficiency measures in practice. This scheme is designed to decrease the use of energy in each Member State, making sure that all distributors of energy and/or retail energy sales companies designated as obligated parties subject to Article 7 (4) achieve a cumulative end-use energy saving target. The target is a 1.5% yearly decrease of the annual energy sales to final customers of all energy distributors or all retail energy sales companies by volume, and may alternatively be met through certified

[83] See Recital 55.

[84] Recital 3 of Directive 2012/27/EU.

[85] See Article3 3 (1).

[86] Article 3, paragraph 1 (d) of Directive 2012/27/EU.

[87] See Recital 13.

savings stemming from energy service providers or other third parties.[88] Amongst the obligated parties identified under Article 7 (4) are energy distributors, retail energy sales companies, transport fuel distributors and transport fuel retailers, making these requirements not only relevant, and potentially challenging, for CCU in general but also specifically for synthetic fuels, given the energy intensity recorded for these products. Annex V of the EED establishes basic principles on the methodology for determining the efficiency and energy savings.

In November 2016 the Commission put forward a proposal for a new EED (EED II). According to the Commission, the main provisions to be revised are: raising the binding target for reduced energy consumption to 30%; an extended energy savings obligation for the period 2021–2030, with an updated and amended methodology for calculating energy savings; new requirements for the metering of natural gas, district heating, cooling and domestic hot water; and greater transparency and reinforced rights to accurate information on actual consumption.[89] The obligation to make a 1.5% energy saving per year is continued in the proposal and there is a flexibility for the Member States on how to implement this obligation, either through the energy efficiency obligation scheme as mentioned above or other measures.[90] This leaves room for taking national conditions into consideration.

The importance of increased efforts regarding energy efficiency is emphasised in the Explanatory Memorandum to the proposal, stating that 'energy efficiency needs to be considered as a source of energy in its own right.'[91] In the Memorandum it is further stated that the proposed amendments are unlikely to have any major impact on metering and billing for energy consumers.[92][93]

The proposed new Annex V provides common methods and principles for calculating the impact of the energy efficiency schemes or other policy measures subject to Article 7(1) and (2), Article 7(a) and (b), as well as Article 20(6). In Article 1(a)–(c) there are several alternatives for calculating energy savings: deemed savings, metered savings, scaled savings or surveyed savings. Article 2(a)–(h) gives the basic principles. As a consequence of the proposed principles, requirements to develop quality standards for the shortlisted products may occur if the technologies reach a commercial stage. The Member States must, according to Article 2(f), ensure such standards are maintained, or introduced if non-existent, to promote the taking up of energy efficiency measures.

We have not observed any direct hurdles or incentives in the EED for the shortlisted technologies. The EED seems, both in its current and proposed new form, to be technology neutral. However, as many of the CCU technologies demand intensive use of energy for production, including those for the production of synthetic fuels, mineralisation and polymerisation processes, the shortlisted CCU technologies may challenge the targets of the EED. Although this does not represent a direct hurdle for the deployment of CCU technologies, it may imply that Member States will be reluctant to support large-scale deployment of such

[88] See Article 7 (4) and (7)(b).

[89] http://www.europarl.europa.eu/oeil/popups/summary.do?id=1467007&t=e&l=en, www.europarl.europa.eu/legislative-train/theme-resilient-energy-union-with-a-climate-change-policy/file-energy-efficiency-directive-review

[90] See Proposal for a Directive of the European Parliament and of the Council amending Directive 2012/27/EU on energy efficiency (Text with EEA relevance) – COM(2016) 761 Final, Explanatory Memorandum, page 2.

[91] See Proposal for a Directive of the European Parliament and of the Council amending Directive 2012/27/EU on energy efficiency (Text with EEA relevance) – COM(2016) 761 Final, Explanatory Memorandum, page 2.

[92] See Proposal for a Directive of the European Parliament and of the Council amending Directive 2012/27/EU on energy efficiency (Text with EEA relevance) – COM(2016) 761 Final, Explanatory Memorandum, page 4.

[93] www.europarl.europa.eu/oeil/popups/ficheprocedure.do?reference=2016/0376%28COD%29&l=en

technologies or to introduce policies to support them, or to approve permit application and provide funding for further technology development. However, the consideration of early action and potential for energy storage in, for example, synthetic fuels may weigh positively in the national assessments.

3.3.6 Directive 2009/28/EC on Renewable Energy (the RED) and its recast, Directive 2018/2001/EU (RED II)[94]

The Renewable Energy Directive (the RED) is a framework for the promotion of energy from renewable sources through, for example, mandatory national targets for the share of energy from renewable sources, and rules for statistical transfers between Member States, access to the electricity grid and joint projects between Member States and third countries, see Article 1. The RED also establishes sustainability criteria for biofuels and bioliquids.

On 17 February 2017 the Commission proposed a recast of the Renewable Energy Directive (RED II). Following the adoption of the general approach by the Council, the European Parliament adopted an opinion on 17 January 2018,[95] and an agreement was reached in June 2018.[96] This recast will enter into force on 1 January 2021.

Under the RED it is considered '*appropriate to support the demonstration and commercialisation phase of decentralised renewable energy technologies*'.[97] Such support comes in different forms, depending on the national implementation and may include encouraging the exchange of best practice and promotion of the use of structural funding.[98] National support schemes are one of the tools available to reach the targets under the RED[99] and the guarantee of a proper functioning national support schemes is considered to be an important measure by the Directive itself.[100]

The potential for fuels from CO_2 and renewable energy to help integrate renewable energy into the transport sector is recognised in the 2009 Directive by the requirement that at least 10% of all transport fuels in all Member States should come from renewable sources by 2020. RED II subsequently increased that percentage share to 14% by 2030.[101]

RED II includes two types of fuels as eligible pathways to meet the 2030 target which are relevant in a CCU context: recycled carbon fuels and renewable fuels of non-biological origin.

[94] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (Text with EEA relevance).

[95] http://www.europarl.europa.eu/oeil/popups/summary.do?id=1519347&t=e&l=en

[96] Directive 2018/2001/EU of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance)

[97] See RED Recital Article 6.

[98] See RED Recital Article 4.

[99] See RED Article 3(3)(a).

[100] See RED Recital 25.

[101] Directive 2018/2001/EU of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance)

RED II defines recycled carbon fuels as

> liquid and gaseous fuels that are produced from liquid or solid waste streams of non-renewable origin which are not suited for material recovery in line with Article 4 of Directive 2008/98/EC and waste processing gases and exhaust gases of non-renewable origin which are produced as an unavoidable and not intentional consequence of the production process in industrial installations'.

This definition affects the range of fuels which may be exempted from other emissions reduction schemes, such as the ETS. It aims to avoid double counting of emissions reductions.

Renewable fuels of non-biological origin are fuels '*whose energy content comes from renewable energy sources other than biomass, and which are used in transport*' (such as in power-to-fuel technologies).

RED II lays the foundations for the methodology for accounting renewable energy input in the production of fuels originating from renewable energy sources, and the determination of which fuels count as renewable. The detailed methodology is yet to be developed; however, several principles have been laid down under which renewable energy share can be determined when electricity is sourced either from the national grid or directly from a power-generating installation.

For instance, '*the methodology should <u>ensure that there is a temporal and geographical correlation between the electricity production unit</u>, which the producer has a bilateral renewables power purchase agreement with, <u>and the fuel production</u>.'* (our underlining; preamble 65a).

The specific conditions are also outlined in the legislation:

- When using electricity sourced from the grid, 'either the average share of electricity from renewable energy sources in the Union or the share of electricity from renewable energy sources in the country of production, as measured two years before the year in question, may be used to determine the share of renewable energy' (Article 25(3)). In Article 25(3) it is stated that

  > electricity that has been imported from the grid may be counted as fully renewable if the electricity is produced exclusively from renewable energy sources and the renewable properties and any other appropriate criteria [ ] have been demonstrated, ensuring that the renewable properties of this electricity are claimed only once and only in one end-use sector.

- While Article 25(3) states that only

  > electricity obtained from direct connection to an installation generating renewable electricity (i) that comes into operation after or at the same time as the installation producing the renewable liquid and gaseous transport fuel of non-biological origin and (ii) is not connected to the grid or is connected to the grid but can provide evidence that the respective electricity has been provided without importing electricity from the grid, can be fully counted as renewable electricity for the production of that renewable liquid and gaseous transport fuel of non-biological origin.

With regard to the first condition (bullet point above), it is relevant to note that the current share of renewable energy is not expected to be sufficiently high to account for fuels produced from the grid as fully renewable. For this reason it is possible that CCU fuels will never be counted as renewable if electricity is used from the grid according to this requirement, except in some Member States where renewable energy sources prevail in the power generation sector and not in the transport sector.

The rationale for the second condition is that currently existing renewable energy should not be diverted from its current uses in order to avoid the opportunity cost of producing rather energy inefficient CCU fuels,[102] compared to more efficient energy sources, such as hydrogen or direct electricity usage. The requirements mean that a CCU fuel production installation should come complemented by a new and additional renewable electricity production installation not connected to the grid. This raises the likely costs of producing CCU fuels counted as renewable and requires the availability of renewable energy production capacity in the vicinity of CCU fuel production.

Furthermore, RED II sets the greenhouse gas emission savings required from liquid and gaseous transport fuels of non-biological origin to be counted as renewable (excluding recycled carbon fuels) to be at least 70% as of 1 January 2021 (Article 25(1)). This percentage share has been criticised by stakeholders as extremely difficult to achieve.

3.3.7 Directive 2009/30/EC on Fuel Quality (the Fuel Quality Directive, FQD)[103]

The regulatory framework for the decarbonisation of fuels in the EU is mainly governed by two instruments: the Fuel Quality Directive (the FQD) and the RED (discussed above). The FQD applies to petrol, diesel and biofuels used in road transport, and gasoil used in non-road-mobile machinery. Together with the RED, the FQD establishes rules to help reduce greenhouse gas and air pollutant emissions, as well as mechanisms to establish a single fuel market and ensure that vehicles can operate everywhere in the EU on the basis of compatible fuels.[104]

The FQD regulates the greenhouse gas intensity of the fuels and establishes minimum specifications for petrol and diesel fuels. The FQD provides rules for the maximum percentage of certain types of biofuels (e.g. ethanol in petrol, see, for example, Article 3) and also regulates the sustainability of biofuels together with the RED.

The FQD establishes the following target:

> Suppliers should, by 31 December 2020, gradually reduce life-cycle greenhouse gas emissions by up to 10% per unit of energy from fuel and energy supplied. This reduction should amount to at least 6% by 31 December 2020, compared to the EU-average level of life-cycle greenhouse gas emissions per unit of energy from fossil fuels in 2010, obtained through the use of biofuels, alternative fuels and reductions in flaring and venting at production sites. Subject to a review, it should comprise a further 2% reduction obtained through the use of environmentally friendly carbon capture and storage technologies and electric vehicles and an additional further 2% reduction obtained through the purchase of credits under the Clean Development Mechanism of the Kyoto Protocol. These additional reductions should not be binding on Member States or fuel suppliers on entry into force of this Directive. The review should address their non-binding character.

[102] Source: interview with the European Commission.

[103] Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EE.

[104] https://ec.europa.eu/clima/policies/transport/fuel_en

When calculating the intensity of GHG of fuels the emissions from extraction, processing and distribution are included, and the intensity is calculated on a life-cycle basis.[105] CCU fuels can count to the target set out under the FQD, provided that they deliver greenhouse gas savings, see, for example, Article 7a, and provided that GHG default values are established for the given type of fuel.

When it comes to establishing GHG default values regarding the GHG reductions Article 7a[106] subparagraph 6 points out that (our underlining):

> The Commission shall be empowered to adopt no later than 31 December 2017 delegated acts in order to establish greenhouse gas emission default values, where such values have not already been established prior to 5 October 2015, as regards:
> (a) renewable liquid and gaseous transport fuels of non-biological origin; [107]
> (b) <u>carbon capture and utilisation for transport purposes</u>.

The default values were established for other types of fuels through Council Directive (EU) 2015/652 of 20 April 2015 laying down calculation methods and reporting requirements pursuant to Directive 98/70/EC of the European Parliament and of the Council relating to the quality of petrol and diesel fuels.[108] According to an interview with the Commission, the methodology for setting the default values referred to in Article 7a, paragraph 6, has been established based on work performed by the Joint Research Centre; however, no values have been adopted yet, because the methodology should be aligned with that applicable under RED II, which is still in the co-legislative process, in particular as regards the way in which to account for the share of energy from renewables for the production of e-fuels (see the Section above on the RED).

The need for default values have also been promoted by elements of industry.[109]

Currently there are no plans on extending the GHG reduction target beyond 2020, as provided for in the FQD, and the Commission has proposed instead that the revised RED should include targets for low carbon and renewable transport fuels until 2030.[110] This implies that RED II is the Directive under which after 2020 the methodology for CCU fuels will be most relevant. Given the limited time left until the application of the FQD target in 2020, default values under the FQD are likely to have a limited impact on the market.

The FQD allows conventional petroleum products to be blended with methanol at a rate of 3% by volumetric concentration. According to renewable methanol producers, it is technically possible to blend up to 10%. However, the compatibility of such fuel with existing engines would need to be considered. Whilst this is a potential restriction on the rate of renewable methanol supply, current consumption of petroleum by motor vehicles in Europe is excess of 8 billion litres, which would place a cap at about 250 million litres of methanol just for motor vehicles. Presently the ambitious plans of Europe’s largest producer of renewable methanol in Europe

[105] https://ec.europa.eu/clima/policies/transport/fuel_en

[106] Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009.

[107] Amended by Directive (EU) 2015/1513 of the European Parliament and of the Council of 9 September 2015 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources (Text with EEA relevance) Article 1 (10).

[108] https://ec.europa.eu/clima/sites/clima/files/transport/fuel/docs/novel_transport_fuels_default_values_en.pdf

[109] http://co2-chemistry.eu/CCU-petition/

[110] https://ec.europa.eu/clima/policies/transport/fuel_en

(CRI) amount to 50 million litres per year, so this unlikely to be a barrier to renewable methanol production in the near-term.[111]

3.3.8 Directive 2009/31/EC on the geological storage of carbon dioxide (the CCS Directive)

Directive 2009/31/EC on the geological storage of carbon dioxide (in general referred to as the CCS Directive) regulates '*environmentally safe geological storage*' of CO_2, see Article 1. The CCS Directive is first and foremost relevant for CCS, or CO_2 capture, transport and storage. However, the wording *'environmentally safe storage'* of CO_2 includes any carbon capture and storage process, provided that the CO_2 is stored geologically, fully or in part, including situations in which the CO_2 has been utilised prior to storage. In general, this is referred to as CCUS, or CO_2 capture utilisation and storage. CO_2-EHR (enhanced hydrocarbon recovery), which is not part of this study, is an example of a CCUS technology that is covered by this Directive, see Recital paragraph 20. The ETS Directive applies to CO_2 being stored in accordance with the CCS Directive, see the ETS Directive Article 2, see Annex I, meaning that the emissions caused by and removed as consequence of CCS and CCUS will be counted against the allowances and thus subject to trading. For the CO_2 stored to be eligible for allowances under the ETS Directive it has to be considered *'permanently contained',* see the CCS Directive, Article 1(2) and 18(1)(a). Liability for climate damage as a result of leakages or emission of CO_2 from a CCS operation is covered by the inclusion of storage sites in the ETS Directive, which requires the surrender of emissions trading allowances for any leaked emissions. The link between the CCS Directive and the ETS Directive is meant to create incentives for the CCS/CCUS industry.

From a geological point of view there is no such thing as '*permanent*'. There have therefore been numerous attempts to establish or define what this requirement implies. As of now, there is no specific time period linked to the term '*permanent*', although it seems like a time period in the range of around a thousand years would generally be assumed to meet the requirement (Global CCS Institute, 2014). To our knowledge, the IPCC was one of the first to make an attempt to define this period in their Special Report on CCS; *'[w]ith regard to global risks, based on observations and analysis of current CO_2 storage sites, natural systems, engineering systems and models, the fraction retained in appropriately selected and managed reservoirs is very likely to exceed 99% over 100 years, and is likely to exceed 99% over 1000 years.'* (IPCC Special Report)

For the shortlisted CCS technologies the question is whether they could be eligible under the CCS Directive and thus access the ETS regime for financial incentives. To answer that question it is necessary to analyse the potential for permanent removal of CO_2 from the atmosphere. As observed in Task 1, certain shortlisted CCU products do offer relatively long-term carbon storage; such products include calcium carbonate and polymers. Of the longer term uses for calcium carbonate, using the carbon dioxide molecule in the production of concrete for the construction sector is likely to offer the longest retention time. Polymers also have different possible usages, including plastic coatings, plastic bags, and laminates. Depending on the final fate of the material, this use could represent storage of carbon of several decades or centuries. However, this storage duration does not meet the characteristics of permanence presented by, for example, the IPCC and would fall outside the scope of the CCS Directive. Furthermore, most of these materials would not end up being injected in geological formations and would thus fall outside the scope of this regime regardless of retention time. We have therefore not analysed the CCS Directive in more detail.

[111] Ecofys and Carbon Counts. (2013). Implications of the Reuse of Captured CO_2 for European Climate Action Policies. By order of European Commission DG Climate Action. p.82.

3.3.9 Decision 406/2009/EC on the effort of Member States to reduce their GHGs (the Effort Sharing Decision)

The Effort Sharing Decision was introduced as a part of the EU Climate and Energy Package, which was proposed by the EC in January 2008, and entered into force in June 2009. The main targets of the Climate and Energy Package were to reduce the EU's GHG emissions by at least 20% below 1990 levels by 2020, and to achieve a share of 20% of renewable energy, something that was expected to be achieved through a combined effort of the ESD, the ETS, the RED, the CCS Directive, a regulation on CO_2 emissions from cars which set mandatory CO_2 standards for new vehicles and an amendment to the FQD (Forster et al., 2016).

The ESD establishes binding annual greenhouse gas emission targets for Member States for the period 2013–2020 with regard to most sectors not included in the EU ETS Directive, see Articles 1 and 3, in particular the categories as defined by Annex I of the ESD; energy, in the form of fuel combustion and fugitive emissions from fuels, industrial processes, solvents and other product use, agriculture and waste. The ESD does not cover emissions from land use, land use change and forestry and international shipping, and a study conducted in 2018 concluded that there was a '*potential lack of coherence between the ESD and other interventions in relation to agriculture and land use, land use change and forestry (LULUCF).*' (Forster et al., 2016) These concerns have subsequently been addressed, resulting in the new LULUCF regulation. This regulation is dealt with in our analysis in Section 3.4.11 below.

In more detail, the ESD covers the emissions of six greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6), see Article 2. Thus this framework is relevant for several of our shortlisted technologies. Having such a wide application, it may be relevant if the CO_2 in the given CCU project comes from a sector that is not covered by the ETS regime. For several of the technologies identified in the shortlist this would be the case.

It is up to each Member State to limit its emissions in accordance with the ESD by introducing policies and further making use of the flexibility that is found within the ESD's provisions, see Article 3(2)–(5) and Article 5. The flexibilities enable, for example, Member States to transfer annual emissions allocations to other Member States or to move such forward to the next year if not consumed in a given year. A more thorough assessment of this flexibility can be found in Section 3.4.10 on the Effort Sharing Regulation, as the flexibilities are continued in the new regulation that will apply for emissions after 2020.

It was expected the ESD would lead to additional GHG mitigation actions being taken by Member States in order to meet their respective emission limits. In a study analysing the effectiveness of the ESD it was concluded that the ESD has delivered its objectives efficiently by, for example, stimulating the implementation of national polices but that it has been difficult to quantify the impact that the ESD has had on emission reduction. The study also found that "The coherence of the ESD with other EU Climate and Energy policies is strong." Furthermore, there was no evidence of national policies under the ESD having affected competition in the EU internal market by the date of the study in 2016 (Forster et al., 2016). The report also states that stakeholders interviewed for the study noted a strong coherence between the objectives of the ESD and the EU objectives relating to energy efficiency and renewable energy.

It was further concluded there was a need to reduce administrative burdens under the ESD (Forster et al., 2016). After a review of the ESD, we have not found that any of the administrative burdens seem to be a hurdle for CCU technologies or our shortlist in particular. Furthermore, we did not note any of the administrative burdens being hurdles as such, regardless technology. Nevertheless, some of these administrative burdens have been eased under the new Effort Sharing Regulations, as analysed in chapter 3.4.10 below. We have therefore not analysed these further.

We have not detected other hurdles in the ESD relevant to the shortlisted technologies, nor any specific incentives. Potential hurdles or incentives could potentially be observed at the national level. The stakeholder consultations did not produce any reports of such national hurdles or incentives.

3.3.10 Effort Sharing Regulation 842/2018 on binding annual greenhouse gas emission reductions between 2021 and 2030

On 20 July 2016 the European Commission presented a legislative proposal, the Effort Sharing Regulation (the ESR), setting out binding annual greenhouse gas emission targets for Member States for the period 2021–2030, taking over from the ESD. The Regulation was adopted on 30 May 2018, setting national emission reduction targets for 2030 for all Member States, ranging from 0% to –40% from 2005 levels. The targets are based on principles of fairness, cost-effectiveness and environmental integrity (EC Climate Action, Effort Sharing 2021–2030).

The Regulation maintains existing flexibilities under the Effort Sharing Decision in relation to, for example, banking (see Article 5(3) of the proposal), borrowing (see Article 5(2) of the proposal), buying and selling (see Article 5(4) and 5(5) of the proposal) annual emission allocations. These flexibilities allow the Member States to bank their net surplus of allocated emissions for later years or to trade with other Member States. This provides flexibility to meet annual fluctuations in emissions as, for example, production is scaled up or down. These flexibilities are according to the information included in the explanatory memorandum of the proposal untested and further offer a lot of scope to reduce costs and achieve cost efficiency (see Article 5(1) of the proposal).

The ESR further provides two new flexibilities to allow for a fair and cost-efficient achievement of the targets: the one-off flexibility to access allowances from the EU ETS (see Article 6 of the proposal); and to access credits from, and transfers to, the land use sector (see Article 7 of the proposal). The latter is regulated by the new LULUCF regulation as analysed in Section 3.4.11 below. Given the close ties between the ESR and the LULUCF Regulations, these two instruments have been discussed and prepared in parallel in the EU (European Council press release 17 January 2018), with the result that the flexibilities between the two instruments are closely coordinated.

In relation to access to credits under the ETS, there is a limited and predefined volume of 100 million tonnes available to cover some emissions in the non-ETS sector with surplus ETS allowances that would otherwise be auctioned off (EC Climate Action, Effort Sharing 2021–2030). It was identified under the impact assessment of the proposed ESR that the flexibilities relating to the EU ETS and LULUCF had to be limited in order to secure real mitigation action in the non-ETS sector. As a response to that, the proposal limits the additional removals from deforested land, afforested land, managed cropland and managed grassland to 280 million tonnes CO_2 net removal (see Article 7 of the proposal).

The flexibilities included in the new Regulation will in theory make possible Member States allocating more allowances to industrial sectors comprised by the shortlist, creating more flexibility to engage in technology development and scale up production. As it is to a large extent left up to national implementation and priorities with regards to how this flexibility should be used, and as it would be a sector-related flexibility and not an available flexibility for the individual industries or stakeholders, it is at this stage not feasible to assess the exact effect of these flexibilities.

According to the EC, the ESR aims at reducing the administrative burden, similar to that proposed by the report by Forster et al. (EC Climate Action, Effort Sharing 2021–2030). The proposal first and foremost affects national administrations and there are no direct reporting obligations or other administrative consequences for private stakeholders. Potential effects are possible for private stakeholders as well, depending on national implementation. As national implementation falls outside the scope of this assessment, we have not analysed this aspect in more detail. It is worth noting, however, that we have not detected any proposed national administrative burdens that seem to pose hurdles with regard to the deployment of the CCU technologies on the shortlist, nor has the stakeholder consultation resulted in any reports thereof.

3.3.11 Land Use, Land Use Change and Forestry, Decision 529/2013 and Regulation 841/2018

On 20 July 2016 the European Commission presented a legislative proposal for a regulation on the inclusion of greenhouse gas emissions and removals from land use, land-use change and forestry (LULUCF). On 14 December 2017 the European Parliament and Council reached a provisional agreement, on 17 April 2018 the European Parliament adopted the proposal and, finally, the regulation was formally adopted by the Council on 14 May 2018 (EP Legislative Observatory, Procedure file 2016/0230(COD). On 30 May 2018 Regulation 841/2018 was adopted, amending Decision 529/2013/EU. The regulation will enter into force 20 days after its publication in the Official Journal (European Council Press release 17 January 2018).

The regulation incorporates and introduces greenhouse gas emissions and removals related to agricultural land and forestry into the EU's climate framework from 2021 by recognising land and forests as carbon sinks (EC Climate Action, Latest News 14 December 2017). Together with the ESR and the revised ETS directive, the new Regulation creates a binding legal framework for the EU's efforts to reduce overall greenhouse gas emissions by at least 40% by 2030 compared to 1990 levels and is thus the third pillar of the 2030 climate and energy framework (EC Climate Action, Latest News 14 May 2018). According to the EC's own assessment, *'[t]he new rules will provide Member States with a framework to incentivise more climate-friendly land use, without imposing new restrictions or red tape on individual actors'* (EC Climate Action, Land use and forestry regulation for 2021–2030).

The LULUCF Regulation does not regulate any of the technologies on the identified shortlist and whether or not the regulation poses barriers for the industries and activities comprised therefore falls outside the scope of our assessment. In relation to our shortlisted technologies, it is in particular the flexibility to allocate emissions from the LULUCF Regulation to the Effort Sharing Regulation and vice versa that is relevant and subject to our assessment. When a Member State has net emissions from land use and forestry, it can use allocations from the ESR for it in one of the five-year periods, and the shortfall is deducted from the ESR allocations, see the LULUCF regulation Article 12(1)–(3) (European Parliament legislative resolution of 17 April 2018). This flexibility is thus left with the Member States to handle within certain limits.

The flexibility between the LULUCF and the ESR seemed to be well received by the industries covered by the LULUCF, as in particular agriculture has limited emission reduction potential (summary of stakeholder feedback with regard to the Land Use, Land Use-Change and Forestry (LULUCF) proposal). This is also recognised by the EU, as the proposal allows for more flexibility for Member States with a larger share of emissions from agriculture (EC Climate Action, Effort Sharing 2021–2030).

This would in theory make it possible for Member States to allocate more allowances to industries on the shortlist by allocating allowances to the industrial sector covering the industries, creating more flexibility to engage in technology development and scale up production. However, with regard to the ESR the consequences of this allocation are hard to predict, as these are not stakeholder-specific allowances. If total removals exceed emissions within the LULUCF, the Member States may choose to transfer (i.e. sell) the surplus allowances to other Member States, see the proposed language of the LULUCF Regulation Article 11(2)–(3) or bank the surplus to the next period, see the proposed language of the LULUCF Regulation, Article 11(3). The flexibilities therefore seem to follow the same model as under the ESR, making the transfer of allowances between the two schemes easier.

As it is to a large extent left up to national implementation and priorities with regards to how the flexibilities under the regulation should be used, it is at this stage not feasible to assess the exact effect of the flexibility provided for in the proposed LULUCF might have on CCU technologies.

3.3.12 EU Action Plan for a circular economy

The European Commission's Circular Economy Package (COM(2015) 614 final) was presented in December 2015. It includes four legislative proposals on waste, revising six pieces of legislation and a communication ('Action Plan for the Circular Economy – Closing the loop') (the CEAP). The Circular Economy Package and the CEAP aim to 'close the loop' by complementing the measures contained in the legislative proposals and to contribute to meeting the United Nations Sustainable Development Goals (the SDG) adopted in 2015, in particular Goal 12 on sustainable consumption and production. Key actions, both legislative and non-legislative, put forward in the action plan include:

- actions to reduce food waste, including a common measurement methodology, improved date marking, and tools to meet the global Sustainable Development Goal to halve food waste by 2030;
- development of quality standards for secondary raw materials;
- measures in the Ecodesign working plan for 2015–2017 to promote reparability, durability and recyclability of products, in addition to energy efficiency;
- a new regulation on fertilising products, to encourage nutrient recycling while ensuring the protection of human health and the environment;
- a strategy on plastics in the circular economy, addressing issues of recyclability, biodegradability, the presence of hazardous substances in plastics, and the Sustainable Development Goals target for significantly reducing marine litter;
- a series of actions on water reuse, including a legislative proposal on minimum requirements for the reuse of wastewater;
- a fitness check of the Ecolabel.

The CEAP states that its aim is to ensure that the right regulatory framework is in place for the development of the circular economy in the single market, and to give clear signals to economic operators and society at large on the way forward with long-term waste targets as well as a concrete, broad and ambitious set of actions to be carried out before 2020. Action at the EU level will drive investments and create a level playing field, remove obstacles stemming from European legislation or inadequate enforcement, deepen the single market, and ensure favourable conditions for innovation and the involvement of all stakeholders.[112]

The CEAP lists actions to be taken by 2020, according to the main phases of the product life-cycle: production, consumption and waste management, and recycling. Furthermore, the CEAP highlights 'priority areas', including specific waste streams, for which it identifies necessary actions. The aspects of the CEAP which are relevant for CO_2-based products will be discussed according to this structure.

With regard to the production phase, the CEAP states that it is important to promote innovative industrial processes. For example, industrial symbiosis allows waste or by-products of one industry to become inputs for another. In its revised proposals on waste, the Commission proposes elements to facilitate this practice, and will engage with Member States to help ensure

[112] European Commission, Closing the loop – An EU action plan for the Circular Economy, COM(2015) 614 final, Brussels, 2 December 2015, p. 2

a common understanding of the rules on by-products. Furthermore, the CEAP mentions the reuse of gaseous effluents, in particular CO_2, as another example of innovative process.[113][114]

With regard to the recycling phase, the CEAP mentions that the Commission will launch work to develop quality standards for secondary raw materials where they are needed (in particular for plastics), and is proposing improvements to the rules on 'end-of-waste'. As will become apparent in the Section concerning the Waste Framework Directive (2008/98/EC), this action would be highly relevant for CO_2-based products to enhance legal certainty and create a level playing field for CO_2 based products operation on the internal market.[115]

With regard to the priority stream plastics, the CEAP announced a strategy addressing the challenges posed by plastics throughout the value chain and taking into account their entire life-cycle. This strategy was published by the European Commission in January 2018. The CEAP aims regarding plastics have been further substantiated in the EU Strategy for Plastics in a Circular Economy. This strategy addresses the main challenges for a circular plastics chain, as well as opportunities.[116]

In its vision for Europe's new plastics economy, the strategy envisages that innovative materials and alternative feedstocks for plastic production will be developed and used where evidence clearly shows that they are more sustainable compared to the non-renewable alternatives. This supports efforts regarding decarbonisation and creating additional opportunities for growth.[117]

The strategy states that alternative feedstocks include bio-based feedstocks and gaseous effluents (e.g. carbon dioxide or methane) and that these can also be developed to avoid using fossil resources.[118] Based on the available scientific information, the Commission will look into the opportunities for supporting the development of alternative feedstocks in plastic production.

Finally, the strategy mentions the role of R&D in developing alternative feedstock and that the Commission will develop a Strategic Research and Innovation Agenda on plastics to provide guidance for future research and innovation funding after 2020.[119]

To support these developments the Commission has already proposed new rules on waste management. These include clearer obligations for national authorities to step up separate collection, targets to encourage investment in recycling capacity and to avoid infrastructural overcapacity for processing mixed waste (e.g. incineration), and more closely harmonised rules on the use of extended producer responsibility. The Commission has consistently called on the co-legislators to swiftly agree on these new rules. Once adopted and implemented, this new European legislation should do much to improve the current situation, driving public and private

[113]European Commission, Closing the loop – An EU action plan for the Circular Economy, COM(2015) 614 final, Brussels, 2 December 2015, p. 5.

[114] http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52018DC0028&from=EN

[115]European Commission, Closing the loop – An EU action plan for the Circular Economy, COM(2015) 614 final, Brussels, 2 December 2015, p. 11.

[116]European Commission, Closing the loop – An EU action plan for the Circular Economy, COM(2015) 614 final, Brussels, 2 December 2015, p. 14.

[117]European Commission, A European Strategy for Plastics in a Circular Economy, COM(2018) 28 final, Brussels, 16 January 2018, p. 5.

[118]European Commission, A European Strategy for Plastics in a Circular Economy, COM(2018) 28 final, Brussels, 16 January 2018, p. 14.

[119]European Commission, A European Strategy for Plastics in a Circular Economy, COM(2018) 28 final, Brussels, 16 January 2018, p. 14.

investment in the right direction. However, additional and more targeted action is needed to complement waste laws and remove barriers that are specific to the plastics sector.

With this in mind, the Commission is committed to working with the European Committee for Standardisation and the industry to develop quality standards for sorted plastic waste and recycled plastics.

To date we have observed no restrictions on current production methods involving CCU technology in comparison to conventional methods. Possible amendments can be expected in general in plastics production, with regards to substances hampering recycling processes, that might be replaced or phased out in future years.

Mining waste is among the largest waste streams in the EU and some of that waste is dangerous. The Commission considers the waste produced from extractive industries to be a major problem. Further, the resources extracted will not be available for future generations. [120] Mining can thus be considered a contradiction to European Union's Circular Economy Package. Mining is an industry based on extraction, so even if CO_2 is being reused and therefore can be seen as a part of the circular economy package the mining part is not in line with the principles of circular economy. As a result, a wide range of instruments that will be dealt with in the following Sections, relating to waste management, pollution control, etc, are relevant for the mineralisation process involving mining.

3.3.13 Directive 2008/98/EC on waste (the Waste Framework Directive, WFD)[121]

The Waste Framework Directive (2008/98/CE, the WFD) lays down measures to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste and by reducing overall impacts of resource use and improving the efficiency of such use.

As such, the scope of the WFD covers '*waste*', which is defined by Article 3(1) as '*any substance or object which the holder discards or intends or is required to discard*'. The CJEU has determined in its case law that whether a substance or object is in fact waste within the meaning of the Directive must be determined in the light of all the circumstances, regard being had for the aim of the Directive and the need to ensure that its effectiveness is not undermined.[122]

The broad definition of waste, resulting from the WFD and CJEU case law, has the potential to cover many substances or objects which have reached the end of their life-cycle. Once meeting the definition of '*discarding*', they are considered waste and are consequently subject to provisions concerning, inter alia, permitting, licensing and transport.

One of the main ideas behind the legal framework for waste is that waste, due to its end-of-life properties and circumstances, could pose a risk for human health and the environment. The potential presence of substances of concern, such as chemicals and heavy metals, in waste is one of such risks which could be relevant for the case of CO_2-based products.

[120] Communication from the Commission promoting sustainable development in the EU non-energy extractive industry. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=legissum:l28113

[121] Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance).

[122] *ARCO Chemie Nederland Ltd v. Minister van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer*, Joined Cases C-418/97 and C-419/97 [2000] E.C.R. I-04475 para. 73.

The practice of understanding what is '*waste*' (as opposed to non-waste, the latter including industrial by-products and substances/objects which are considered end-of-waste, see below) varies between Member States. Certain Member States consider the materials processed into CO_2-derived products (potentially the CO_2 itself, but more likely other input materials) as waste. Under this classification the production process could be classified by Member State authorities as a recycling process. Recycling is defined by the WFD as being any recovery operation by which waste materials are reprocessed into products, materials or substances, whether for the original or other purposes. That includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations.

If the authorities of a Member State classify a CCU operation as recycling, a subsequent question will be under which circumstances the product resulting from this recycling can be considered to have acquired end-of-waste status, as provided in Article 6 of the WFD. Upon acquiring end-of-waste status a substance or product will leave the legal framework applicable to waste and will enter the framework applicable to products and chemicals legislation. Article 6(1) determines that certain specified waste will cease to be waste when it has undergone a recovery, including recycling, operation and complies with specific criteria to be developed in accordance with conditions provided under (a) to (d):

- (a) the substance or object is commonly used for specific purposes;
- (b) a market or demand exists for such a substance or object;
- (c) the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and
- (d) the use of the substance or object will not lead to overall adverse environmental or human health impacts.

Article 6(4) furthermore determines that where criteria have not been set at EU level, Member States may decide case by case whether certain waste has ceased to be waste, taking into account the applicable case law.

No specific end-of-waste criteria have been set for CO_2-based products. Therefore it is for the various Member States to determine their own specific criteria, based on Article 6 of the WFD, or to determine on a case-by-case basis whether the general criteria of Article 6 of the WFD are met.

With regard to the case-by-case application of end-of-waste criteria for CO_2-based products, the literature indicates a need for harmonisation among Member States.[123] Lack of harmonised application might lead to a lack of a level playing field for CO_2-derived products in the internal market, and at least in theory with problems in case of transboundary shipments between two Member States with regard to which one considers the transported material to be waste while the other one considers it having become end-of-waste. Furthermore, the variation in application may cause legal uncertainty for CCU operators as to the status of CO_2-based products and therefore the applicable legal requirements. Finally, there is a chance that authorities in Member States might not allow the placing of a given CO_2-based product on the market. It should be mentioned here that the varying application of the end-of-waste criteria is a broader issue which affects more secondary raw materials and recycled products. The European Commission has acknowledged the importance of arriving at a more harmonised application of the end-of-waste criteria in its Circular Economy Action Plan (CEAP) (see 3.3.12 above).

[123]Wilson et al. (2016). A Strategic European Research and Innovation Agenda for Smart CO_2 Transformation in Europe. SCOT Project. p. 32.

In addition to the lack of harmonised application of end-of-waste criteria, some of the specific criteria under Article 6 might create challenges for CO_2-based products, due to their novelty. Firstly, paragraph (a) of Article 6(1) requires that the substance or object is commonly used for specific purposes. As mentioned above, the innovative nature of CCU and CO_2-based products might lead relevant authorities in Member States to conclude that criterion (a) is not satisfied. However, as will become apparent under Section 3.4.2 (on policy options), this point might be remedied by the envisaged amendment of Article 6 under the Circular Economy package.

Another potential obstacle for CO_2-derived products could be criterion (c) of Article 6 of the WFD, which requires that the substance or object resulting from a recycling process satisfies the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products. Due to the novelty of CCU, it might not be clear which regulatory frameworks or technical standards are applicable to CO_2-based products. In this regard, other analysed legislation in this chapter might be relevant, such as the REACH.

The absence of applicable product legislation will render criterion (c) less relevant for competent authorities, and likely increase the emphasis of the end-of-waste assessment on criterion (d), which requires that the use of the substance or object will not lead to overall adverse environmental or human health impacts. This is a broad requirement, which, in the absence of product regulations and technical standards to provide guidance, might be more difficult to satisfy. Furthermore, certain input materials used to produce CO_2-derived products may contain certain substances of concern, such as heavy metals, or substances which are suspected of posing a risk for human health and the environment. In this case, the relevant authorities in the Member States may, on the basis of the precautionary principle, consider criterion (d) of Article 6 of the WFD not met. Furthermore, it is also possible that the Member State authorities will consider criterion (d) not met, despite the fact that the given CO_2-based product satisfies the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products (i.e. meets criterion (c)). This could be the case if the applicable product standards and regulations do not regulate certain waste-related risks for human health and the environment which the CO_2-based product poses or might pose.

3.3.14 Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (the Industrial Emissions Directive, IED)

Adopted on 24 November 2010, the Industrial Emissions Directive, or IED, became the main EU instrument regulating an integrated approach to pollution arising from industrial installations, providing rules for prevention and control of emissions into air, water and soil, as well as to waste management, to energy efficiency and to accident prevention, see Article 1. The IED represents a consolidation of EU frameworks on these issues, seeking to '*prevent, reduce and as far as possible eliminate pollution arising from industrial activities*'. The Directive is based on the polluter pays principle and the principle of pollution prevention, see Recital 2. It is an integrated part of the EU's effort sharing legislation, applicable next to the EU ETS Directive, seeking to ensure an overall compliance with the different national emission targets for Member States, regarding both GHG and pollutant emissions. The interrelations between the IED and ETS Directives has been more closely commented on below.

The IED applies to a wide range of industries and is relevant for CCU technology routes. With regard to the list of activities in Annex I, the IED covers most of the technologies contained in the shortlist, e.g. production of cement (see Annex I (3.1)), chemical industry (see Annex I (4)), plastic materials as polymers (see Annex I (4.1)(h)), waste management connected mining in the mineralisation process (see IED Annex I (5)) and energy industries (see Annex I (1.4)). The IED is therefore an important instrument with regard to our analysis.

Article 2.2 of the IED exempts '*research activities*', '*development activities*' and the '*testing of new products and processes*', meaning that these activities will not be subject to the Directive. Thus for further development and testing of CCU technologies as referred to in Section 2 (Task

1) above the restrictions and requirements of the IED will not apply. However, that does not imply that these activities are not subject to regulations and restrictions or that the CCU technologies at a point in time prior to commercialisation may not be affected by the IED. There is, however, room for derogation from the requirements for the testing and use of emerging techniques, see Article 15. Thus the IED seems to go to great lengths to accommodate technology development and new technologies, as long as the technologies or activities do not imply an unnecessary or excessive increase of pollutant emissions, for example a requirement in Article 15 to either stop the activities after the temporary period or ensure that the emissions do not exceed the targets of the IED. These flexibilities allow for the need to continue the technology development as referred to in Section 2.4 above (Task 1.2) and further identification and development of future value chains, see Section 2.4.2.1.

Annex II of the Directive lists the polluting substances that might be subject to restrictions, see, for example, Article 14(1)(a), regarding *'emission limit values for polluting substances listed in Annex II, and for other polluting substances, which are likely to be emitted from the installation concerned in significant quantities, having regard to their nature and their potential to transfer pollution from one medium to another.'* CO_2, as a greenhouse gas, is not regulated as a pollutant under the IED, its emissions restricted under the ETS Directive. Task 2.1 has not had access to the full list of substances included in the shortlisted technologies and we have therefore not been able to perform a full analysis of the potential hurdles related to the polluting substances. However, we have noted that there could be potential restrictions for the CCU mineralisation process. As summed up in Task 1, the source for the CaO is either standard cement kiln (Meyer et al., 2017), slag from steel furnaces (Quaghebeur et al., 2015), sewage (Calera Coperation, 2017) or dust residues from a waste incineration plant (Carbon8 Systems, 2017). In Annex II (6) dust including fine particulate matter is defined as a pollutant. Beyond limitations with regard to the emission limit values for these substances, there are, depending on the type and size of installation, requirements to monitor (see Article 38), control (see Article 46) and seek authorisation to change operating conditions (see Article 51). We have not noted any direct hurdles with regard to these requirements and have performed no further analysis of the pollutants under the IED.

However, the IED sets out a wide perspective with regard to its definitions of both '*pollution*' in Article 3(2) and emission limit values for selected pollutants. Emission limit value is defined as *'the mass, expressed in terms of certain specific parameters, concentration and/or level of an emission, which may not be exceeded during one or more periods of time*,' see Article 3(5).

The IED requires the use of best available techniques (BAT) to meet the emissions limit values, see Article 15(2), see Article 14(1)–(2). *'Emission levels associated with the best available techniques' has its own definition in Article 3(13): 'the range of emission levels obtained under normal operating conditions using a best available technique or a combination of best available techniques, as described in BAT conclusions, expressed as an average over a given period of time, under specified reference conditions'*. As BAT is an important element of the IED it has been analysed in some detail below.

The definition of BAT is found in Article 3(10):

> 'best available techniques' means the most effective and advanced stage in the development of activities and their methods of operation which indicates the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent and, where that is not practicable, to reduce emissions and the impact on the environment as a whole:
>
> - *(a) 'techniques' includes both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned;*
> - *(b) 'available techniques' means those developed on a scale which allows implementation in the relevant industrial sector, under economically and*

technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator;

- *(c) 'best' means most effective in achieving a high general level of protection of the environment as a whole.*

In relation to the shortlisted CCU technologies the question is whether they can be categorised as BAT and be taken into consideration when setting the emission limits values for such pollutants as listed in Annex II, restricted under the IED.

Based on the information available to Task 2.1, our preliminary observation is that none of the CCU routes are classified as BAT at the present. Even if more data was available for Task 2.1, potentially resulting in conclusions that the CCS routes could qualify as BAT, this would not automatically result in the technologies being taken into consideration for the emission limit values, see the definition of emission levels associated with the best available techniques, requiring the technology to be described in BAT conclusions. *'BAT conclusions'* is defined in Article 3(12) as '*a document containing the parts of a BAT reference document laying down the conclusions on best available techniques, their description, information to assess their applicability, the emission levels associated with the best available techniques, associated monitoring, associated consumption levels and, where appropriate, relevant site remediation measures*'. The BAT reference documents, in which the BAT conclusions are part, are drawn up, reviewed and updated in co-ordination between the Commission and the Member States, see Article 13. Our preliminary analysis has not identified any of the CCU routes in the existing BAT reference documents. This implies that the CCU routes are excluded from being taken into consideration as tools to meet emission limit values until the technologies are potentially included in the BAT conclusions.

The IED must be considered in co-ordination with the EU ETS Directive. As Article 11 of the IED also applies to the industrial activities listed in Annex I to the EU ETS Directive, Article 9 seeks to ensure an overall compliance. A permit given pursuant to the IED will, as a general rule, not include emission limit values for activities already covered by Annex I to the ETS Directive, see Article 9(1) of the IED. The reasoning therefor is avoidance of double emissions counting, illustrating the connection between these regulations. Following the integrated approach, permits must also take into account the entire environmental performance of the industrial activity. Article 9(2) further provides the option of not applying energy efficiency requirements to EU ETS installations (Department of Environment, Food and Rural Affairs, 2013). As our preliminary conclusion is that the CCU routes are not eligible as a tool to set emission levels associated with the best available techniques, the risk of double counting is not relevant for the shortlisted technologies under the IED.

As the obligation to hold a permit in itself is not a hurdle to initiating activities, and all of the criteria to be included in the permits are performance-based and technology neutral, this will not be subject to further analysis. There is, however, potential for national hurdles regarding permits, as nationally competent in that the competent authorities are granted a lot of leeway with regard to the IED, both in relation to the granting of permits and the contents thereof and criteria therefor. The IED provides minimum criteria and procedures which Member States may deviate from. However, there are also certain minimum requirements in relation to the granting of permits included in the wording of the IED, providing a safeguard for industry if they satisfy the requirements of the IED. Thus the national authorities may not refuse to grant a permit if the requirements are at that time met. Furthermore, the IED requires competent authorities to co-ordinate with regard to permitting if the activity in question is subject to more than one jurisdiction or permitting authority. These provisions provide mitigation of potential lack of predictability for industry and streamline the national restrictions as far as possible. There is still, however, room for national authorities to, under certain circumstances, set stricter permit conditions than those provided in the IED, see, for example, Article 14(4).

The IED also contains requirements with regard to monitoring (for example Articles 16, 38 and 63), reporting (for example Article 23, 59 and 62), how to handle site closures (Article 22), environmental inspections (Article 23) and transboundary effects (Article 26), to mention but a few. Annex IV establishes criteria for public participation in decision making, which is first and foremost to ensure that the public concerned will be entitled to submit comments and opinions to the competent authority before a decision, such as the granting of a permit related to activities subject to the IED, is taken. This process is not meant to expose industry to the risk of sharing sensitive information but instead to ensure that the public concerned will be informed of any potential harmful or polluting activities that are or might be initiated in proximity to them and that they are allowed to express their concerns and have their questions answered. Such requirements are not, however, to be considered as hindering of new technology.

For a more specific analysis of the shortlisted technologies possible hurdles with regard to the IED may be found in, for example, the market clusters for bulk chemicals, fuels and polymers, and with regard to the prior CO_2 conversion required. The CCU transformation routes are various, with hydrogenation, electrolysis and photosynthesis being some of the different transformation processes which require energy and hydrogen from renewable sources. In comparison to conventional fossil-based methods, the Technologies Assessment indicates a higher energy demand and material intensity. This means that, despite the CO_2 emissions savings, CCU-based products and routes may conflict with the IED with regard to the obligations regarding energy and material savings. As concluded in Section 2.6 above, this was in particular a problem for electrolysis. As explained in the Sections relating to the Energy Efficiency Directive and the Effort Sharing Decision and regulation, this might be the case for more than the IED.

To sum up the findings of the analysis of IED, the CCU routes are not eligible as tools to set the emissions limit values, as they are not defined as BAT or emerging technologies under the IED, which regards pollutants in comparison to GHG emissions, regulated under the ETS. Furthermore, the CCU technologies are not eligible to reduce the pollutants which the IED seeks to reduce. This may present, if not a hurdle, a lack of incentive to deploy these technologies. Additionally, the energy intensity and increased raw material consumption during the production of several of the technologies may be contrary to the obligation to reduced emissions and consumption.

3.3.15 Regulation 1907/2006/EC concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)

REACH is the European Regulation on the Registration, Evaluation, Authorisation and Restriction of Chemicals and it replaced the former framework for chemicals in the EU. Also, as the full name indicates, REACH established the European Chemicals Agency, to '*ensure effective management of the technical, scientific and administrative aspect*', see REACH Recital Article 15. This framework imposes responsibilities with regards to the risks concerning chemicals and providing information on those risks in industry. Although the focus is on chemicals, the framework covers more industries than just the chemicals industry. REACH addresses the production and use of chemical substances and establishes obligations for manufacturers, importers and downstream users, see Article 1(3) as it applies to '*the manufacture, placing on the market or use of such substances on their own, in preparations or in articles and to the placing on the market of preparations*', see Article 1(2).

The priorities of the framework are to '*ensure a high level of protection for human health and the environment, including the promotion of alternative test methods, as well as the free circulation of substances on the internal market and the enhancement of competitiveness and innovation*', see Article 1(1). REACH requires co-operation between companies and Member States, enhancing communications along the supply chain, as well as providing tools to guide and assist companies and public authorities with regard to its implementation (EC DG Growth, REACH). REACH also imposes reporting (for example Articles 10, 14, 17(2), 22(1) and 31(2)), control (for example Articles 14(6), 17(3), 18(4) and 37(4)) and monitoring (for example Articles 47(2), 60(8) and (9), and 127) measures to ensure compliance.

Annex XIV of REACH sets out the list of substances subject to authorisation, whilst Annex XVII sets out restrictions on the manufacturing, placing on the market and use of certain dangerous substances, preparations and articles. Based on the information given in Task 1, we have not noted any listed substances in the CCU routes, implying that the shortlisted products as such are not subject to relevant restrictions. However, we have not performed a full case-by-case analysis of the technology routes, as we have not have had access to the full chemicals inventory for all of the routes, and are therefore not able to rule that out completely.

With regard to the production of polymers REACH sets forth specific provisions. Polymers are generally regarded as a group of substances of low concern. According to Title II of REACH, see Article 2.9 polymers are generally exempted from registration and evaluation. The manufacturer or importer of a polymer is therefore generally not required to provide to the Agency any information related to the intrinsic properties of the polymer itself.

As CO_2 in itself is an inert substance, CCU processes often require reactants in the form of chemical substance additives. Additives can be needed to preserve the stability of the polymer (stabilisers), as well as other substances to improve the polymer’s performance. Stabilisers are regarded as part of the substance itself and do not require separate registration, whilst other additives are, however, not regarded as part of the polymer and may be subject to specific obligations. Polymers may be synthesised not only from the polymerisation of monomers but also from other processes, such as the chemical post-modification of polymer substances. Such other technological processes have not been analysed in more detail for Task 2.

Even though polymers are generally exempted from registration, they may, therefore, still be subject to authorisation and restriction if they – or any substance used in the process of producing them – are listed. Depending on the substance used and its classification under the regulation, obligations with regard to registration, evaluation, authorisation and even restriction of use for some dangerous chemicals, referred to as substances of very high concern (SVHC), can occur.

Provided that no new materials or toxins are added to a CCU process, the overall observation is that the REACH framework does not pose a barrier to the deployment of the CCU technologies on the shortlist as such. The framework first and foremost covers formal obligations of registration, communication and other administrative requirements.

Following recent EU proposals methanol is to be included in a new entry 69 of Annex XVII (the European Chemicals Agency, Registry of Intentions). The entry will only restrict the use of methanol in certain mixtures, i.e. windscreen washing or defrosting fluids and denatured alcohol. Thus, depending on how the methanol is utilised, it may be subject to future restrictions.

3.3.16 Regulation 66/2010 on the EU Ecolabel

The EU Ecolabel is a third-party certified Type I ISO 14024, see Article 11, established in 1992. Regulation 66/201 on the EU Ecolabel (the Ecolabel Regulation) was adopted 25 November 2009, aiming to replace Regulation (EC) 1980/2000 of the European Parliament and of the Council of 17 July 2000 on a revised Community eco-label award scheme, see Recital 1–3, see Article 18. The purpose of the Ecolabel Regulations is to continue the voluntary EU ecolabel award scheme for the promotion of products with a reduced environmental impact.

The Ecolabel Regulation lays down the rules for the establishing and application of the EU ecolabel, see Article 1, setting market-oriented and science-based criteria. These criteria will take into consideration the latest technological developments as well as the entire life-cycle of the products, see Article 6(3). Every four years, on average, the criteria are revised to reflect technical innovation such as evolution of materials, production processes or in emission reduction and changes in the market (EC DG Environment, the Ecolabel).

The EU Ecolabel covers a wide range of products, see Article 2(1). Only food, drinks, and medical and pharmaceutical products fall outside of its scope, see Article 2(2), see Recital 6. The product groups can be summarised as personal care products, cleaning products, clothing and textiles, do-it-yourself items, electronic equipment, coverings, furniture, mattresses, gardening equipment, household appliances, lubricants, other household items, paper products, and holiday accommodation. Furthermore, product groups covering food and feed products, as well as office buildings, are under development (EC DG Environment, Product Groups and Criteria) The Ecolabel criteria are tailored to each product group and extended in many cases for separate products under each product group, as the life-cycle of every product and service is different, and cover all phases of the given product from manufacturing to use and end of life. For example, the criteria for bed mattresses provided in a Commission Decision dated 23 June (Decision 2014/391/EU) and criteria *for 'hard coverings'*, meaning covering *'for internal/external use, without any relevant structural function – natural stones, agglomerated stones, concrete paving units, terrazzo tiles, ceramic tiles and clay tiles*' are regulated by Commission Decision 2009/607/EC.

Article 6 provides general requirements for the EU Ecolabel criteria in 1–3 (our underlining below):

- 1 – EU Ecolabel criteria shall be based on the environmental performance of products, taking into account the <u>latest strategic objectives of the</u> Community in the field of the environment.
- 2 – EU Ecolabel criteria shall set out the <u>environmental requirements</u> that a product must fulfil in order to bear the EU Ecolabel.
- 3 – EU Ecolabel criteria shall be determined on a <u>scientific basis</u> considering the <u>whole life-cycle of products</u>.

When determining the criteria as referred to above, factors which need to be taken into consideration include the most significant environmental impacts, replacement of hazardous substances, reduction potential for environmental impacts due to durability and reusability, as well as net environmental balance between environmental benefits and burdens, see Article 6 (3)(a)–(d).

The EU Ecolabel scheme could serve to promote CCU technology if recognised and reflected in the specific criteria, although it is uncertain whether that would have any real consequence for already commercial CCU products (see IEAGHG Technical Review, 2018). The question is thus whether using CCU technology in the production process may be taken into consideration and might ensure the awarding of the Ecolabel. The lack of maturity of many CCU products, the uncertainty regarding the potential environmental benefits of the technologies and the discussion on missing standards for LCA for CCU complicate the analysis and will most likely result in a general conclusion that products manufactured using CCU technology are not eligible as such under the current framework, see the criterion in Article 6(3) on considering the entire life-cycle of the products.

To establish whether some CCU technologies would be eligible for ecolabeling under the criteria thus requires a case-by-case analysis for the CCU routes. Co-ordination must be ensured between the scheme and the establishing of requirements in other directives, see the wording *'shall be based on the environmental performance of products, taking into account the latest strategic objectives of the Community […]'* in Article 6(1). Recital 9 mentions Environment

Action Programmes, Sustainable Development Strategies and Climate Change Programmes as relevant. Thus, the other instruments analysed in Task 2.1 are relevant for the analysis.

We have not performed a full case-by-base analysis for the CCU routes in order to establish potential eligibility under the Ecolabel Regulation, due to the aforementioned lack of data on the environmental benefits of the technologies. Furthermore, this task would require more resources than this project has available. However, it is worth mentioning that products such as the already discussed concrete block aggregates (Carbon8 Systems 2017) would be difficult to fit into the Ecolabel scheme, as not only is the LCA still uncertain, or criteria missing for a standardised LCA, but the Member States also disagree on whether recycling of hazardous waste and using the components in the aggregates satisfy the end-of-waste criteria and result in a '*less hazardous*' product. Seeking eligibility for the aggregates directly challenges the wording of Article 6(3)(b) on considerations to be made when establishing criteria: '*the substitution of hazardous substances by safer substances*'. If criteria or standards are established to close the gap between the way Member States classifying hazardous material, that could potentially open up for an analysis of potential eligibility under the Ecolabel scheme. Also worth mentioning in relation to the Ecolabel scheme is analysis of synthetic fuels, where requirements related to, for example, DAC and energy intensity would potentially challenge the wording in Article 6(3)(d) on considerations to be made when establishing criteria, requiring consideration to be given to '*the net environmental balance between the environmental benefits and burdens*'. Despite the potential for long-term replacement of fossil fuels, currently the resources required to produce synthetic fuels which are eligible for a certificate of origin under RED II may make it hard to meet the requirements under the Ecolabel scheme.

To sum up our findings, the CCU routes analysed for this report, both in general and individually, are deemed to fall outside the Ecolabel scheme. Lack of certainty relating to environmental benefits and standards for LCA are the main reasons for this preliminary conclusion. These gaps could be mitigated by more research and documentation with regard to the benefits as well as through the establishing of the aforementioned missing standards.

3.3.17 Regulation 305/2011 laying down harmonised conditions for the marketing of construction products (the CPR)

Adopted on 9 March 2011, the Construction Products Regulation (the CPR) lays down harmonised rules for the marketing of construction products in the EU, see Article 1. It stablishes harmonised technical specifications for the purposes of assessing the performance of construction products. Furthermore, it requires that reliable information is available to professionals, public authorities, and consumers, so they can compare the performance of products from different manufacturers in different countries.

Manufacturers of construction products must provide declarations of performance, see Chapter II, including testing and calculations, for the assessment of health and safety aspects related to the use thereof during the entire life-cycle. These are first and foremost administrative burdens and, as with the other instruments assessed as part of Task 2.1, we have not noted any of these posing hurdles for the shortlisted technologies as such.

Furthermore, requirements of energy efficiency are provided, see Annex I (6), echoing other Union legislation and policies. Annex I (6) requires '*using as little energy as possible during their construction and dismantling*'. In general, the CCU technology routes included in the shortlist have a higher energy demand than conventional or comparable technologies, which might challenge the satisfying of this provision. On the other hand, the requirement also takes into account the sustainability, reuse and recyclability of the construction work, as well as the use of environmentally compatible raw and secondary materials, see Annex I (7) and Recital 55. This indicates that not only health and safety, but also environmental aspects, are to be taken into account for such performance assessments and might weigh up against the increased energy demand. Thus, a case-by-case assessment of compliance with the Regulation must be made for the performance as a whole, which we have not been performed for the shortlisted CCS Routes.

The basic requirements for *'construction works as a whole and in their separate parts'* are set out in the CPR (Article 3 see Annex I). With regard to hygiene, health and the environment it is required that

> [t]he construction works must be designed and built in such a way that they will, throughout their life-cycle, not be a threat to the hygiene or health and safety of workers, occupants or neighbours, nor have an exceedingly high impact, over their entire life-cycle, on the environmental quality or on the climate during their construction,

see Annex I (3), especially if such work results in the giving off of toxic gases or radiation, the emission of dangerous, volatile organic compounds or greenhouse gases, or any risk damaging water sources. The question is whether these requirements entail obstacles to the production of CCU technology Routes resulting in construction products by classifying any of the products *'a threat to the hygiene or health and safety of workers, occupants or neighbours'*, during either manufacturing, use or destruction.

There are no definitions in the CPR of *'toxic', 'dangerous'* or *'volatile'.* The regulation draws a correlation between the word 'hazardous', which is not defined anywhere in the document either. However, Recital 25 states that

> the specific need for information on the content of hazardous substances in construction products should be further investigated with a view to completing the range of substances covered so as to ensure a high level of protection of the health and safety of workers using construction products and of users of construction works, including with regard to recycling and/or reuse requirements of parts or materials. [124]

Furthermore, the Recital makes clear reference to Member States' rights and obligations pursuant to other instruments of Union law that may apply to hazardous substances, both in general and by name, some of which are included in the Task 2 analysis. Thus, to answer the question, there has to be a case-by-case assessment in co-ordination with horizontal legislative restrictions on GHG and hazardous substances imposed in other legal instruments.

As described in Section 3.4.13 above, the calcium carbonate substitute for concrete block aggregates (Carbon8 Systems 2017) is produced by recovery of waste from incinerations and combustion plants. These products include components that are classified as hazardous and official reports of the UK Government claim the process makes the components 'less hazardous' (Innovate UK, 2 January 2014). This less hazardous waste is suitable for cheaper disposal (UCL, Treating waste with carbon dioxide). Despite its hazardous contents, the process has received end-of-waste status in the UK, see Section3.4.13, and the company itself claims to produce non-hazardous products based on hazardous waste (Gunning, 2014). It was reported during the stakeholder consultation that countries such as Germany have banned import of these products, due to the hazardous components. We have not carried out a legal review of the German framework; however, the reasoning seems to be that the products are deemed not to comply with the end-of-waste criteria in Article 6 of the WFD, nor the requirements in Annex 1 of the CPR. Thus, the products seem to be considered hazardous, or a *'threat to the hygiene or health and safety of workers, occupants or neighbours'.* The challenge for the concrete block

[124] See CRP. Recital 25, referencing Article 31 and 33 of Regulation (EC) 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), Directive 98/8/EC of the European Parliament and of the Council of 16 February 1998 concerning the placing of biocidal products on the market,[8] Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy,[9] Regulation (EC) 1907/2006, Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste,[10] and Regulation (EC) 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures.

aggregates is thus that Union law seems to entail too much flexibility in relation to what should be considered *'hazardous'*, resulting in products being labelled as 'non-hazardous' after recycling hazardous components in one country, while labelled *'hazardous'* in others.

Supporting these findings is the '*Industrial sector study on the utilisation of alternative materials in the manufacture of manufactured aggregates*' compiled by Derren Cresswell, stating that '*Legislative barriers are seen from the composition of waste, in particular with materials that have been classified as hazardous (municipal solid waste incinerator fly ash for e.g.)*' (Cresswell, 2007). Although not specified by country and written in 2007, long before the products received their end-of-waste status in the UK, it emphasises that this is a well-known problem for the products.

This lack of harmonisation between Member States could potentially pose a hurdle to the free movement of goods between Member States for the analysed concrete block aggregates. However, without having detailed information on the national implementation of UK or German law and the reasoning behind the different approach to the classification, drawing a clear conclusion is not possible at this stage. Local conditions with regard to groundwater, fauna, local pollution, etc may further result in a need for a different approach to the classification of hazardous products and components.[125] Also, according to Recital 3, the '*Regulation should not affect the right of Member States to specify the requirements they deem necessary to ensure the protection of health, the environment and workers when using construction products*', meaning it should be permitted for Member States to impose stricter rules on hazardous or dangerous substances than the minimum requirements provided for in the Union law. The question to be investigated for the future therefore seems to be whether there are grounds to consider the components in the concrete block aggregates for a harmonised standard, see Recital 13, or potentially by the adaptation of measures in accordance with the principle of subsidiarity as set out in Article 5 of the Treaty on European Union, see Recital 58, or whether these national restrictions are justified.

3.3.18 Regulation 850/2004 on persistent organic pollutants (the POPs Regulation)

Adopted on 29 April 2004, the Persistent Organic Pollutants (POPs) Regulation primarily concerns environmental protection and the protection of human health, see Recital 1. POPs are organic compounds resistant to environmental degradation which pose a risk to both human health and the environment. The POPs Regulation takes into account the precautionary principle, while protecting human health and the environment from POPs by prohibiting, phasing out as soon as possible, or restricting the production, placing on the market and use of substances subject to the Stockholm Convention or the 1998 Protocol to the 1979 Convention on Long-Range Transboundary Air Pollution on Persistent Organic Pollutants, see Article 1(1). The regulation applies in conjunction with, for example, the REACH regime, which is still in force after the implementation of new EU regulations regarding hazardous substances, see Recital 8.

The POPs Regulation provides specific provisions on prohibitions and aims to phase out the production, placing on the market and use of intentionally persistent organic pollutants, including provisions on the disposals and waste management, see Article 5 and Article 7. Furthermore, the POPs Regulation regards release reduction, minimisation and elimination of substances into air, water and land, see for example Article 6 and Annex III.

For waste management, there are restrictions in Article 7, see Annex IV and Annex V, requiring *'producers and holders of waste [to] undertake all reasonable efforts to avoid, where feasible, contamination of this waste with substances listed in Annex IV.'* Furthermore, it is required that

[125] Or as referred to in Recital 13, taking into account 'different levels of basic requirements for construction works for certain construction works as well as of the differences in climate, geology and geography and other different conditions prevailing in the Member States.'

waste that contains POPs '*is destroyed or irreversibly transformed so that the remaining waste and releases do not exhibit the characteristics of persistent organic pollutants*', see Article 7(2). Furthermore, '*[d]isposal or recovery operations that may lead to recovery, recycling, reclamation or re-use of the substances listed in Annex IV*' are prohibited, see Article 7(3), (our underlining). Exceptions may be found in Article 7(4), which, for example, in (b) states that the Member States '*in exceptional cases, [may] allow wastes listed in Annex V, part 2 containing or contaminated by any substance listed in Annex IV up to concentration limits to be specified in Annex V, part 2, to be otherwise dealt with in accordance with a method listed in Annex V*.' This exception permits, for example, fly ash from co-incineration containing dangerous substances to be permanently stored only in a) safe, deep, underground, hard rock formations, 2) salt mines or 3) a landfill site for hazardous waste, see Annex V, part 2, and Article 7(4)(b). This exception is subject to the requirements of the POPs are '*destroyed or irreversibly transformed*' and are not opened to, for example, recycling or re-using.

Taking into consideration that for Task 2.1 it is not completely clear which substances are involved in the Carbon8 process and are considered by Germany hazardous, and thus prohibited, the restrictions in Article 7 of the POPs Regulation on waste management may be part of an overarching hurdle to the free movement of aggregates, working together with the restrictions observed in the WFD and the CPR. Annex V, part 2, draws links between dangerous substances contained in fly ash with Directive 91/689/EEC on hazardous waste, which was later repealed by Directive 2008/98/EC, indicating that the dangerous or hazardous substances comprised by this restriction and exception are not limited to substances listed as POPs. It seems that while the UK considers that it has been demonstrated that the hazardous substances are destroyed or irreversibly transformed by the recycling process, Germany is of the opposite opinion, i.e. that the temporary storage of the substances in aggregates is an unacceptable solution under the POPs Regulation.

Many POPs are used as pesticides, solvents, pharmaceuticals and industrial chemicals, and POPS are also used in a wide range of consumer products. A preliminary analysis of the lists of substances given in Annexes I–IV did result in any findings of substances involved in the CCS routes. We have therefore not noted any further hurdles for the shortlisted technologies presented by this Regulation. However, to conclude whether any of the restrictions in the POPs Regulation apply it would be necessary to carry out a more thorough analysis of the end-user products resulting from, for example, bulk chemicals. Furthermore, as the POPs Regulation works in conjunction with other instruments, such as REACH and Directive 2008/98/EC, substances that are identified under these would potentially lead to further restrictions under the POPs Regulation.

3.3.19 Financing programmes and instruments

As discussed in Section 2.2.5 (Task 1), EU financing programmes and instruments currently exist which can finance CCU projects at various development stages, from research and demonstration to scaling up and implementation. In this Section we review the current use of EU finances for investing in CCU technologies in order to understand which types of projects have so far been funded, to identify gaps in funding, and to provide recommendations on future EU financing decisions to support promising CCU technologies.

Due to the current early stage of development of CCU technologies, most EU financing has to date contributed to research and development (FP7, Horizon 2020 and RCSF). However, in the future break-through technologies may become eligible for financing scale-up and implementation in, for instance, energy-intensive industries and for the larger scale production of CCU-based products. Below we analyse the use of EU research and innovation funding for CCU.

By way of the FP7 and Horizon 2020 programmes the EU has invested over €240 million in CCU projects.[126] The majority of these projects aimed at researching and developing CO_2-based fuels (methanol and ethanol), chemicals (polymers) and/or microalgae, sometimes involving the use of renewable energy. Mineralisation processes are still under-represented in EU-funded research projects.

The RCSF has also contributed to CO_2 capture projects in the coal and steel industry, including 'calcium looping' processes where CO_2 from combustion gasses is captured in a calcium-based sorbent and re-heated to produce pure CO_2, or in oxyfuel combustion for steel processing, also allowing to capture very pure CO_2.[127] These technologies offer the opportunity to use the CO_2 for either utilisation or storage.

The relative imbalance of the financing for CCU technologies could be addressed by the new Innovation Fund as a major possible source of funds. That Fund is further discussed in Section 2.3.3 above (Task 1.1) and 3.4.3 below.

To sum up, there remain some opportunities under EU financing programmes for targeting CCU and a balance across the types of technologies financed should be reached so that their potential can be proven and achieved.

3.3.20 Conclusions of Task 2.1

In the following paragraphs is a summary of our main findings under Task 2.1, first as observations made regarding CCU technologies in general and further as sorted by cluster.

<u>General observations</u>

The EU framework is, in general, flexible and robust. It is well-equipped to accommodate new CCU technologies; however, outstanding issues pertain to recognising CCU under the EU ETS. Very few direct hurdles were observed, both for CCU in general and for each technology route.

Currently one of main hurdles for the large-scale deployment of environmentally-beneficial CCU technologies is their cost. For that reason a supportive EU policy should focus on providing mechanisms and incentives to 'push' and 'pull' the technologies to maturity and to markets, whether through financial support or market mechanisms. As the main market mechanism to mitigate carbon emissions and support decarbonisation of industry is the EU ETS, stakeholders expect the ETS to be able to support CCU technologies in the future. As the analysis in Task 2.1 has shown, the ETS is not currently able to provide that support, due to the difference in carbon accounting used under the ETS and the accounting that is needed to ascertain avoided emissions from CCU processes. Recognising CCU in the current design of the ETS would pose the risk of undermining the integrity of the system by potentially enabling internal carbon leakage and possible double counting of avoided emissions.

A more fundamental question remains: whether the EU ETS is the right policy instrument to incentivise CCU, in particular where other mechanisms could be used. Counting the emissions reductions in the ETS would shift the burden from industrial installations onto sectors addressed under effort sharing legislation.

A key difference between the ETS and effort sharing legislation is that the ETS has a built-in market incentive mechanism, in the form of the carbon market that it creates, where installations in ETS sectors only need to purchase and surrender allowances equivalent to their

[126] Excluding 10 projects for which insufficient information could be found, as reported by Bardow and Green (2018).

[127] Information based on a list of project communicated directly to the consultant.

levels of emissions and can build greater competitive advantage the more carbon-efficient they are. By contrast, effort sharing legislation relies on other policies in its sectors to provide market incentives, such as RED II for transport.

Other issues were identified in the analysis which pertain rather to a missing incentive than a hurdle, such as the novelty of the technologies and the procedures leading up to the inclusion in the BAT reference documents, which currently exclude the shortlisted technologies as eligible tools to set the emission limit values.

For certain technologies, particularly construction aggregates made using CCU processes, national implementation of EU legislation might result in a lack of harmonisation and potential barriers to the proper functioning of the internal market. These findings in general support the observations made Task 1.3, inter alia that legal aspects are not the main barriers to the deployment of CCU.

Below are findings sorted by product cluster.

Bulk chemicals

Bulk chemicals are various and subject to a wide range of regulatory frameworks, especially as many of these are intermediate products to be included in other products. Instruments ranging from the REACH, POPs and CLP Regulations to Seveso III, the WD, the WFD, as well as the energy and climate framework as regulated in instruments such as the IED, the EED and the ETS Directive, are all relevant to bulk chemicals.

As for all chemicals and materials, CO_2-based products have to be comparable to conventional products in terms of mechanical, physical and chemical performance. We have not noted any specific legal barriers to chemicals included in the shortlisted CCU routes as such.

Polymers

Polymers are, as chemicals, subject to a wide range of regulatory frameworks, ranging from production to end-of-use, including instruments such as REACH for registration, CLP Regulations regarding classification and labelling, the WFD, as well as the energy and climate framework as regulated in such instruments as the IED, the EED and the ETS Directive.

During our analysis of the EU framework, we have not noted any specific legal barriers to the production of polymers made with CO_2. This aligns with the findings of Task 1.3, which did not report on any specific market barriers, since polymers are connected to efficiency improvements and are economically competitive with conventional polymers.

Fuels

Fuels are, as are the other CCU routes, subject to a wide range of regulatory and policy instruments, due to the variation of substances, processes and stakeholders involved. As we have not received any information about hazardous substances being components in the fuels, the most relevant instruments for this study have been the FQD, RED/RED II, the IED and the EED, as well as the Ecolabel Directive. In Task 1.3 it was observed that all fuel-related products will strongly depend on policy support, see Section 2.4.1. Furthermore, it was concluded that the source of CO_2 and the provision of renewable energy at a comparable price were important influencers for all of the CCU technologies. The findings in Task 2.1 support these observations and further conclude that these are constraints particularly relevant for fuels.

Renewable Energy Directive II has been revised, leading to CCU fuels being subject to be counted towards national renewable energy targets and supported by the fuel blending quotas if they are recognised as renewable. The methodology for assessing greenhouse gas emission savings from renewable liquid and gaseous transport fuels of non-biological origin and recycled carbon fuels still has to be adopted by means on a delegated act. The methodology for determining whether a CCU fuel can be counted as renewable includes specific conditions following the principles that new and additional renewable energy is used or that energy from the national grid can be proven to be produced exclusively from renewable energy sources. Details have to be determined in a delegated act.

Furthermore, the energy intensity of this technology challenges the rationale of the EU's policies on energy efficiency. This has to be balanced against the potential for reduction of use of fossil raw materials and potential for economic growth and what is found of the potential positive effects on the climate and environment when produced at scale, replacing conventional fuels. The findings of Task 2.1 seem to indicate that the existing framework enables this kind of balancing exercise, resulting in these fuels being acceptable under the EU's policies. That being said, the requirements synthetic fuels seem to face under the RED and the FQD create commercial challenges for the deployment of these fuels.

Mineralisation

With regard to mineralisation we have noted two interlinked potential barriers, which are not barriers to the production of the components or products as such but instead barriers to the proper functioning of the internal market. As observed in Section 3.3.13, concrete block aggregates have received an end-of-waste status under Article 6 of the WFD in the UK but this status does not necessarily apply to all European countries. Not having all the background information on national implementation and the reasoning behind such prohibition, we have observed that some countries, such as Germany, have stricter criteria for the classification of these products, preventing the hazardous waste recycled and used to produce the aggregates from entering the market. Thus, importing these products into Germany is not allowed, as that would potentially be considered importing hazardous waste or products. In relation to this we have further observed that this lack of harmonisation potentially results in the products being classified as dangerous and a *'threat to the hygiene or health and safety of workers, occupants or neighbours'* under the CPR.

As noted in the analysis in Section 3.3.8 regarding the CCS Directive, mineralisation is also a type of technology that would be most natural to consider as a CO_2 storage tool, given that its potential retention time is substantially longer than for all of the other of the CCU technologies analysed for this report. However, as concluded in Task 1.3, issues related to public perception are not in favour of a correlation of CCU and CCS, implying that mitigation of a lack of recognition for CCU technologies under ETS should be considered somewhere other than in the CCS Directive.

3.4 Task 2.2: Developing policy options

3.4.1 Introduction

In this Section policy options are presented for pieces of legislation analysed above and where barriers or gaps have been identified. Where possible, we describe the options' feasibility, coherence, effectiveness, and impact on the environmental integrity of the EU legal framework. Additionally, the options' potential economic, societal and environmental impacts are outlined. Recommendations for future research are also provided, highlighting the potential issues to be further analysed where that could not be done for this project.

The policy options together compose potential sets of different approaches or packages of measures. Each approach represents a case where one type of policy tool or policy framework is used, in order to draw out possible impacts. A preliminary assessment of potential impacts is provided in this Section when describing the policy options, it is summarised in a separate Section 3.5 (Task 2.3).

The exercise aims to ensure that the policy options are developed, in accordance with a set of principles identified as key by the European Commission, by stakeholders during consultations for this study, and under Task 1.3 above. These key principles include the following needs.

- **Principle 1:** Maintain the integrity of the EU environmental policy framework, particularly with regard to the risk of double counting under energy and climate accounting frameworks.
- **Principle 2:** Avoid technological lock-in effects and account for negative impacts on other environmentally promising technologies, where the phase-out of polluting technologies and replacement by innovative and less polluting alternatives is prevented due to perverse incentives.
- **Principle 3:** Encourage resource efficiency in Europe by replacing less environmentally beneficial conventional production capacity with more beneficial CCU production processes, effectively replacing conventional products with CCU products on markets.
- **Principle 4:** Continue to ensure the technology neutrality of the EU policy framework.
- **Principle 5:** Acknowledge the purpose of most CCU technologies as carbon recycling processes replacing fossil or bio-based production processes, rather than being carbon storage technologies.
- **Principle 6:** Separate incentives to reduce CO_2-intensity of industrial activities (EU ETS) and incentives to recycle CO_2 (circular economy) in acknowledgement of CCU's higher potential for improving circular material flows rather than mitigating climate change.

Before discussing each pathway individually, a number of recommendations are summarised here. These recommendations are common to all pathways and emanate from Task 1 and from stakeholder consultations.

- **Recommendation 1:** Standardised LCA methodologies should be adopted for determining the net CO_2 balance of different CCU products and to inform the implementation of EU policies and EU financing programmes (particularly the RED, Horizon 2020, the Innovation Fund, and other financing programmes).[128]
- **Recommendation 2:** Decisions for supporting specific projects should continue to be made on the basis of specific assessments using above-mentioned standardised or accepted LCA methodologies, due to the fact that results from environmental performance assessments are project-specific.
- **Recommendation 3:** Co-operation between sectors and projects should be encouraged in order to exchange knowledge and share resources, and to facilitate industrial clustering and industrial symbiosis.
- **Recommendation 4:** Foreign diplomatic and policy efforts should be pursued with regard to harmonisation between the ETS and existing or developing national or regional carbon trading schemes, in order to create a level playing field for low-carbon and more expensive products coming from EU industries.
- **Recommendation 5:** CCU should be clearly defined in EU legislation and communications as a carbon-recycling (rather than storage) technology to avoid

[128] Guidelines for LCA (and techno-economic analysis) of CCU have been developed by a consortium of partners from TU Berlin, RWTH Aachen, University of Sheffield and IASS Potsdam, initiated and commissioned by The Global CO_2 Initiative and EIT Climate-KIC. See: https://www.iass-potsdam.de/en/research/development-standardised-guidelines-lifecycle-assessment-carbon-dioxide-conversion

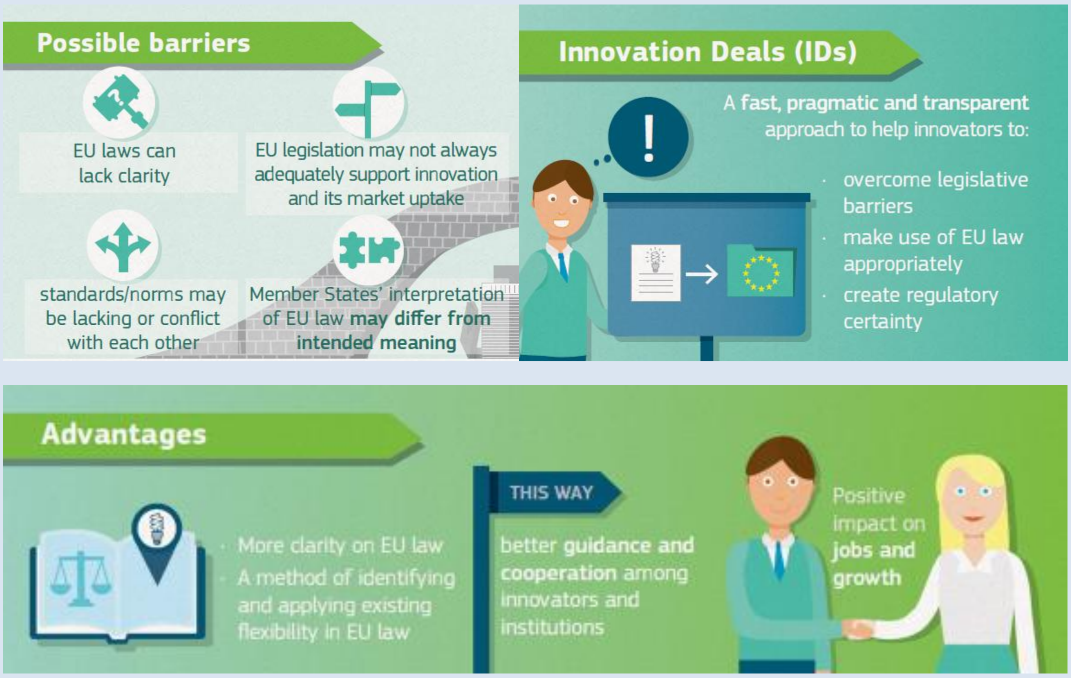
confusion with CCS, and communication should be clear with regard to the environmental performance of CCU technologies.

- **Recommendation 6:** Where perceived barriers to new technologies subsist, Innovation Deals should be used as the new innovation support instrument to guide a stakeholder-led assessment process (described in Box 5 below).

Box 5: EU Innovation Deals.

In 2015 the European Commission announced the introduction under the EU Action Plan for a Circular Economy of new instruments named **Innovation Deals**.[129] These deals can be made following calls for expressions of interest from the Commission and set-up ad-hoc and on a voluntary basis between innovators and relevant regulators at local, national and EU levels to help solve perceived hurdles to innovation originating from EU legislation.[130] The deals aim to either help lift any perceived barrier related to interpretation of the legislation, or use the flexibility in the existing legislation to help innovators achieve their goals and contribute to EU objectives. Innovation Deals cannot lead to derogations from legislation or to amendments.[131]

The figure below shows the types of issues targeted, solutions offered and advantages of Innovation Deals.



The focus of this instrument has so far been on innovation related to the circular economy. As such, the Innovation Deals are very relevant to CCU and could help promising CCU technologies develop and be more widely implemented wherever stakeholders perceive new hurdles.

The alternative pathways to address gaps and barriers and incentivise CCU are summarised below before being described in more detailed in the following Sections.

[129] European Commission, Closing the loop – An EU action plan for the Circular Economy, COM(2015) 614 final, Brussels, 2 December 2015.

[130] European Commission addresses barriers to innovation: the first Innovation Deal focuses on water reuse. Brussels, 7 April 2017. Retrieved from: http://ec.europa.eu/research/index.cfm?pg=newsalert&year=2017&na=na-070417

[131] European Commission. (2018). Joint Declaration of Intent for the INNOVATION DEAL on 'From E-Mobility to recycling: the virtuous loop of the electric Vehicle'. Retrieved from: https://ec.europa.eu/research/innovation-deals/pdf/jdi_emobility_recycling_112017.pdf

1. The EU ETS approach: introducing CCU into the framework offered by the EU ETS

The EU ETS system is first broadly considered under the climate and energy policy framework for revision through the following options:

- **Option 1:** Implementing a project-based accounting approach to CCU projects.

The MRR is more specifically discussed as a possible platform for introducing CCU in the EU ETS:

- **Option 2:** Including CCU through the MR/AV Regulations and Free Allocation Rules.
  - **Option 2.1:** Developing a list of products subjecting installations to possible exemptions.
  - **Option 2.2:** Tracking CCU product transfers.
  - **Option 2.3:** Setting boundaries for single installations or projects to receive exemptions.
  - **Option 2.4:** Granting synthetic fuels to be used in ETS installations similar provisions as for biomass.
  - **Option 2.5:** Extending existing rules for waste gas transfer to CCU.
  - **Option 2.6:** Applying a similar route as heat transfer in the current ETS.

2. A piecemeal approach: recognising the environmental advantages of CCU technologies under other EU policy instruments

Under this approach we build on the existing policy framework identified as relevant and beyond that offered by the EU ETS. The options may not be exclusive.

The products and labelling policy framework offers options to incentivise the market take-up of CCU products, and a number of options were thus identified:

- **Option 1:** Introducing product-blending quotas.
- **Option 2:** Developing a voluntary labelling and certification scheme for carbon-recycled products.

The waste and circular economy policy framework also offers potential options to address existing regulatory barriers and support the market for CCU-based products:

- **Option 3:** Including CCU as part of CEAP objectives and strategies.
- **Option 4:** By-product status for input materials for CCU-based products.
- **Option 5:** Adopting harmonised end-of-waste criteria.
- **Option 6:** Introducing requirements for marketing of CCU goods and defining end-of-waste criteria for secondary raw materials in that context.

The environmental pollution policy framework and the Industrial Emissions Directive in particular are analysed in their potential for additional support to CCU technologies.

- **Option 7:** Identifying CCU as Best Available Techniques or Emerging Techniques.

3. New CCU policy: creating new EU policy specific to CCU

Under this approach new CCU-specific policy would be proposed. One option is considered.

- **Option 1:** Publishing a communication on CCU.

4. A nothing-new policy: only providing EU financing to CCU projects with no further legislation

Under this approach no additional policy would be drafted to change the current framework. However, the EU would continue to provide financing to CCU projects under its existing programmes. Some options for financing are also explored under this scenario.

- **Option 1:** Not including CCU under the EU ETS in any near future.
- **Option 2:** Continuing to support scaling up of CCU technologies via EU financing.

In the following Sections the policy options are explored in more detail.

3.4.2 The Emission Trading System approach: policy options for including CCU in the EU ETS as a carbon reduction measure

Despite the hurdles identified in Section 3.3.3 of the regulatory assessment of the EU ETS, one potential approach can be found in aiming for the inclusion of CCU in the ETS. The options defined under the EU ETS approach propose to change the system offered by the ETS in various ways in order to accommodate climate-beneficial CCU; however, this may be premature considering the uncertainty regarding the environmental benefits and climate change mitigation potential of CCU technologies. For this reason the options proposed here are exploratory and take account of the current state-of-the-art on the technologies.

The preliminary ruling of the CJEU regarding the *Schaefer Kalk* case requires that competent German authorities and the European Commission recognise avoided emissions from the capture of CO_2 and reuse in the production of PCC. This ruling raises a number of issues, identified in Section 3.3.3 above, which need to be addressed prior to allowing installations to report avoided CO_2 emissions, in order to maintain the environmental integrity of the EU ETS.

In order to capture the full potential climate benefit of a CCU technology and accurately attribute incentives under the ETS in compliance with the 'avoided emissions' and 'permanent storage' criteria defined in the ETS Directive (recalled in Section 3.3.3 above), an understanding of the net GHG emission balance of the given CCU process on a cradle-to-gate basis focusing on the key influencing variables (CO_2 sources, energy sources, CO_2 transport) is still needed. The accounting methodology and the incentive system need to:

- take into account accounting for the volume of CO_2 bound in the product and the volume which is released in the CCU process in order to ensure that a tonne of CO_2 emitted is a tonne reported, while a tonne of CO_2 avoided is a tonne deducted;
- consider the use and disposal of the products, and in which sector the product is used and the carbon emitted;
- avoid double counting due to attributing incentives to CCU under the ETS (see Box 6 below) and avoid potential overlap with existing instruments such as the RED.

Box 6: Avoiding double counting due to attributing incentives to CCU under the ETS and avoiding overlap with existing initiatives

A crucial consideration is whether CCU needs to be stimulated through the EU ETS or if other policy instruments are more fit for purpose. The key issue is that carbon emissions avoided from a CCU technique can only be counted once. If CCU fuels are counted as 'zero emission fuels' or 'reduced emission fuels' under RED II and contribute to the targets in the ESR (Effort

Sharing Directive), the capturing of CO_2 cannot be attributed as avoided emission under the ETS, otherwise there would be double counting of avoided emissions.

The key question is therefore which policy mechanism would more effectively incentivise climate-beneficial CCU. This is also a question of relative prices: is the market premium for synthetic fuels likely to be higher in the future than the incentive available through EU ETS? Answering that question goes beyond the scope of this study but may be important to consider if regulatory settings are to be discussed in the future.

In addition, some other considerations may play a role. The general key consequence of allowing CCU processes to be eligible as a carbon reduction measure under the ETS is that some installations within the chain of the carbon flow must be exempt from having to surrender allowances for the CO_2 that has been recycled, or if the CCU product is likely to escape the boundaries of the ETS to go into a non-trading sector (e.g. transport), the system of incentives must avoid double incentives and double counting. There is an ongoing discussion among experts regarding this issue, in this study we simply refer to existing viewpoints.

As pointed out by Bardow and Green (2018)[132] and above in this study, the attribution of ETS incentives depends on the end CCU application. A detailed argumentation of their suggested approach to treating these differences can be found in the original source and is therefore only summarised here.

- In the case of mineralisation of CO_2 into a product used for construction, such as calcium carbonate used in cement, the installation which captures the carbon and binds it into the product is likely to permanently store the CO_2 and should therefore be exempt from surrendering allowances.
- In the case of other CCU products with shorter retention times (such as fuels), the exemption should not be given to the installation capturing the carbon due to the possibility for this carbon to be re-emitted at the end-of-life in a non-ETS sector. Instead Bardow and Green (2018, p. 34) propose that the final installation purchasing and burning the fuel and emitting the CO_2 should receive the exemption if the carbon remains within the boundaries of the ETS. Where the carbon is expected to be emitted in a non-ETS sector (e.g. transport), the EU should propose demand-side incentives, such as quotas for CCU products, to be mixed with other products[133] (as is now allowed under the mechanisms of RED II and the FQD for drop-in CCU fuels).

We have adopted this approach in this study when developing policy options.

We argue that support for CCU processes leading to avoided emissions and maintaining the environmental integrity of the system could be provided if the ETS were to be altered in a fundamental way, or if new and affordable monitoring and verification mechanisms could be introduced.

Since agreement was recently reached with regard to the revised ETS Directive (in February 2018) and the Directive adopted in March 2018, there is little probability of altering the Directive during this phase. It is also important to note that the development of the regulatory framework is dependent on the evolution of technologies and on the knowledge of their environmental impacts. For now the European Commission has made a conscious decision to first support CCU through funding by the Innovation Fund, thereby reusing EU allowances from the ETS, but not fundamentally changing the regulatory approach under the ETS (see the

[132] Bardow, A. & Green, D. (2018). Low-Carbon Process Industries Through Energy Efficiency and Carbon Dioxide Utilisation – A study in support of a DG Research & Innovation Projects for Policy (P4P) report. European Commission Directorate-General for Research and Innovation.

[133] This is explored further in the Section 3.4.3.1 policy option 1.

statement quoted from COM(2015)0337 – C8- 0190/2015 – 2015/0148(COD) in Section 3.3.3 above).

The discussion between experts reflected in the following Sections is still ongoing and has received some attention in other literature.[134] This Report thus reflects the state of the art on policy discussions surrounding CCU, the final direction of which is still unclear, and reflects the uncertainty regarding the environmental effects and the climate change mitigation potential of the technologies. What is clear, however, is that the ETS should not be used as the primary incentive mechanism for CCU at any condition, as that could facilitate regulatory loopholes (internal carbon leakage and double counting or double incentives), particularly where other policy instruments could otherwise be used.

It remains relevant to put forward considerations for future modifications of the system. The discussion presented here is set against the background understanding of CCU processes' climate mitigation benefits described in Task 1 and in Section 3.3.1, and the analysis of the legislations and of the preliminary court judgement of the CJEU in Sections 3.3.3 and 3.3.4. The latter has evidenced a number of problems arising from attempting to include CCU in the EU ETS. Below we investigate two options:

- **Option 1:** Implementing a project-based accounting approach to CCU projects.
- **Option 2:** Including CCU through the MR/AV Regulations and allocation methodology.

Crucial for both options is that the climate benefits of CCU must be clearly determined. Therefore in the first option we address the question of how the ETS could be reformed to take into account the climate mitigation benefit of CCU processes. We investigate second the option of altering the MR/AV Regulations. It should be noted that this discussion should not be regarded as a final solution as to how CCU can be included in the EU ETS, and further research needs to be conducted.

3.4.2.3 Option 1: Implementing a project-based accounting approach to CCU projects

The current ETS is neither able to accommodate the concept of emissions avoided outside the ETS mentioned initially in Recital 14 and further defined in Section 3.3.1 in the context of CCU, nor is it able to properly incentivise the requirement set in Article 10a(8) for CCU projects to deliver a net reduction in emissions and ensure avoidance or permanent storage of the CO_2. We identify this as a key issue to be addressed with regard to accounting for climate benefits of CCU under the ETS.

One approach may be to alter the defined boundaries of GHG accounting in an ETS context in order to allow the accounting for avoided CO_2 emissions outside of a single installation. Such an approach would, however, need to define the nature of the avoided emissions outside the ETS (for example, does the production of an energy saving product by an installation covered under the ETS lead to accountable savings if the saving occurs in a sector regulated in the ESR?). Prior

[134] For instance, Bardow, A. & Green, D. (2018). Low-Carbon Process Industries Through Energy Efficiency and Carbon Dioxide Utilisation – A study in support of a DG Research & Innovation Projects for Policy (P4P) report. European Commission Directorate-General for Research and Innovation.

See also: Wilson et al. (2016). A Strategic European Research and Innovation Agenda for Smart CO_2 Transformation in Europe. SCOT Project.

And: IEAGHG. (2018). Greenhouse Gas Emissions Accounting for Carbon Dioxide Capture and Utilisation (CCU) Technologies. 2018-TR01.

to commencing this discussion, Box 7 below outlines the basics of monitoring of emissions compared to life-cycle-based accounting for CCU.

Box 7: Monitoring of emissions in the ETS versus life-cycle-based accounting for CCU

At present the EU ETS uses monitoring of emissions at the installation level. Companies must submit monitoring report in which they directly measure or estimate the GHG emissions from the activities of their installations. Single installations and their processes are the focus of the monitoring and reporting system under the EU ETS.

However, CCU technologies identified in Section 2 (Task 1) are best assessed using life-cycle-based accounting to express GHG emissions avoided. Some or all of the emission savings may occur outside the ETS. A key difference in accounting for GHG emissions from CCU processes is the approach for applying the boundaries of the system, from the single installation to the wider GHG emissions occurring throughout the production chain from cradle to gate, including type of energy sources, source of CO_2, purification and compression, transport, and conversion of CO_2 into a product. In all those stages additional emissions may play a role in the accounting of the real reduction of CO_2 in the whole chain. This is covered by the performing of an LCA such as that carried out in Task 1.2 of this study.

Furthermore, this approach requires the definition of a reference situation or ‘conventional process’ where fossil- or bio-based feedstock is used, the energy source varies, etc. This may vary over time during the energy transition, as a considerable part of the carbon footprint is currently attributed to electricity generation.

The LCA approach can better be reflected in a project-based approach, taking into account the different installations and processes involved in the making of CCU products.

As described in the box above, by defining the boundaries of GHG emission accounting at the level of a project consisting of multiple installations, it becomes more feasible to capture the climate potential of CCU. Such approaches exist already under the United Nations’ Clean Development Mechanism (CDM).[135] In this Section we do not develop a specific option under the ETS but point to the existing mechanism which is not readily available to provide carbon market incentives to CCU projects under the ETS. Its adaptation to the ETS requires further research and a new MRV approach, with options for the latter described in Section 3.4.2.4 (Option 2) below.

[135] Described in IEAGHG. (2018). Greenhouse Gas Emissions Accounting for Carbon Dioxide Capture and Utilisation (CCU) Technologies. 2018-TR01. Page 45.

<u>The United Nations' Clean Development Mechanism</u>

The CDM contains two Approved Methodologies (AM) relevant to CCU and making ETS installation operators eligible to receive certified emission reduction units (CER) to offset their emissions for those projects which, by replacing fossil-based carbon with recycled CO_2 for the production of CO_2 and its commercial utilisation, lead to avoided emissions in developing countries.[136] The methodology for setting a baseline and monitoring GHG emissions in these types of projects is summarised in the CDM Methodology Booklet[137] and revisions to AM0027[138] and AM0063.[139] These AM describe two specific scenarios:

- AM0027: Replacement of CO_2 from fossil or mineral origin with CO_2 from renewable sources in the production of inorganic compounds.
- AM0063: Recovery of CO_2 from tail gas in industrial facilities to replace the use of fossil fuels for the production of CO_2.

This mechanism is not of direct consequence for European CCU projects. The CDM's focus on developing countries indeed does not make CCU projects in the EU eligible. Furthermore, the CDM will cease to exist as of the expiration of the Kyoto Protocol on 31 December 2020, and will be replaced by the Sustainable Development Mechanism, the functioning of which is still under discussion. The EU has already announced that after 2020 it will not accept the use of international credits (including CER).[140] However, AM0027 and AM0063 set examples of methodologies by which CCU processes can be accounted for in a project-based approach and lead to the issuance of tradable carbon credits.

3.4.2.4 Option 2: Including CCU through the MR/AV Regulations and Free Allocation Rules

The MR/AV Regulations are expected to be updated in early 2020. CCU could be included in these and an analysis of how CCU could be considered in the context of the MRV framework is proposed here.

Key challenges to addressing the three requirements mentioned in Section 3.4.2 with legal solutions are the solutions' legal and practical feasibility. For instance, as mentioned in Section 3.3.3 above, the CJEU suggested that avoiding the escape of CO_2 from the ETS could be prevented by way of the 'powers of review and verification conferred on the competent authorities of the Member States'. However, stakeholders have underlined the practical difficulty and affordability for competent authorities and verifiers to conduct checks in installations which are not part of the ETS scheme or in relation to CCU products originating from a producing installation.

[136] As the authors point out, these mechanisms do not apply to *'those scenarios under which a CO_2-based fuel or product may or may not displace a more carbon-intensive alternative'*. Source: IEAGHG. (2018). Greenhouse Gas Emissions Accounting for Carbon Dioxide Capture and Utilisation (CCU) Technologies. 2018-TR01. Page 45.

[137] UNFCCC CDM. (2017). CDM METHODOLOGY BOOKLET. Ninth edition. Retrieved from: https://cdm.unfccc.int/methodologies/documentation/meth_booklet.pdf

[138] UNFCCC CDM. (n.d.). AM0027: Substitution of CO_2 from fossil or mineral origin by CO_2 from renewable sources in the production of inorganic compounds – Version 2.1. Retrieved from: https://cdm.unfccc.int/methodologies/DB/OE28MVRSBGJUV2CB9UB046N62HJ8CP

[139] UNFCCC CDM. (n.d.). AM0063: Recovery of CO_2 from tail gas in industrial facilities to substitute the use of fossil fuels for production of CO_2 – Version 1.2.0. Retrieved from: https://cdm.unfccc.int/methodologies/DB/NT2ICQVYYXJ1YGSOPV8FLULKNSN74C

[140] European Commission. (n.d.). Use of international credits in EU ETS after 2020. Web. Retrieved from: https://ec.europa.eu/clima/policies/ets/credits_en

Other methods must therefore be found which facilitate decision making of competent authorities regarding products originating from CCU processes, which could enable installations to be exempt from having to surrender their ETS allowances. We have developed a step-wise reasoning to identifying the following six sub-options to include CCU in the ETS MRV framework.[141]

- **Option 2.1:** Developing a list of products subjecting installations to possible exemptions.
- **Option 2.2:** Tracking CCU product transfers.
- **Option 2.3:** Setting boundaries for single installations or projects to receive exemptions.
- **Option 2.4:** Granting synthetic fuels to be used in ETS installations similar provisions as for biomass.
- **Option 2.5:** Extending existing rules for waste gas transfer to CCU.
- **Option 2.6:** Applying a similar route as heat transfer in the current ETS.

Below we investigate these options in more detail.

Option 2.1: Developing a list of products subjecting producing installations to possible exemptions

In order to facilitate the decision making of competent authorities regarding products originating from CCU processes and which could exempt installations from surrendering ETS allowances, one solution would be to develop a list of products accepted as leading to an exemption.

To access such list, the CO_2 contained in the product under review should have no chance of being re-emitted in a non-ETS sector (internal carbon leakage). This means that it must either be known to never escape the scope of the ETS, such as in the case of products produced and used in a same sector under the ETS, or it should be known to permanently store the CO_2. Indeed, in the case that a product permanently stores the CO_2 there will be no emission and therefore no possibility of internal carbon leakage. Even in the case where a product stores CO_2 permanently, the CCU production process should have a negative net GHG emission balance compared to a conventional process in order to be climate beneficial, otherwise the CCU product may be replacing another mineral product which may be performing the same or better than the CCU product in terms of the GHG emissions from cradle-to-gate.

This would require identifying with certainty in which cases the CO_2 will not be released from the CCU product in a sector outside of the ETS. Experts and competent authorities should work to build a theoretical understanding of the fate of the CO_2 in various end-use scenarios for different products, corroborated with practical knowledge of the products' uses. Other criteria may be defined in order to enable products to reach the list, such as the stability of the carbon binding, recyclability, end-of-life that will result in CO_2 not being emitted (such as waste landfilling, or waste incineration with CCS), carbon absorption of a material during life-time, etc. Due to the extreme diversity of CCU processes, the criteria need to be adapted to different contexts, creating additional complexity. These can be very challenging tasks and requirements, due to the variety of possible uses of a product altering the fate of the CO_2, and also due to the diversity of production processes which can lead to varying levels of carbon intensity. Furthermore, a decision would still be needed on the basis of a project-specific LCA from cradle-to-gate to establish the net GHG emission balance (volume of CO_2 avoided).

[141] The options may not be exclusive.

An MRV process would be needed to ensure that an installation claiming the production or use of a CCU product is indeed using processes which show climate benefits. Such a process is described below under option 2.2.

This product-centric approach would not be consistent with the current design of the ETS, as it would deviate from the installation-based approach of the ETS and potentially open a way for the system to be changed and used in unpredictable ways.

This option would have significant costs with regards to:

- producing a mapping of product chains and uses, and for keeping such mapping up to date with technological and market developments;
- conducting LCA of installations' CCU processes.

Overall it appears that a list of CCU products eligible for exemptions does not yield benefits in terms of facilitated decision making for competent authorities investigating whether a certain product, and exemption decisions would still need to be made on the basis of a specific process or installation.

As the German Emissions Trading Authority (DEHST) is currently conducting a study on the definition of criteria for facilitating decision making on which GHG transfers can be recognised as deductible from the transferring installation's emissions by installations and competent authorities under the ETS, we recommend that the European Commission and other competent authorities collaborate with regard to the harmonisation of such criteria at the EU level.

Option 2.2: Tracking CCU product transfers

A complementary option to option 2.1 is tracking the volume of products which are used and disposed of following known possible routes. If products can be tracked from producer to user, then accounting and incentivisation become possible. A few alternative options could be envisaged, involving some form of reporting or certification of CO_2 transfers, including, for instance:

a) requiring that installations using or disposing of a CCU product provide statements on how they have used the products or disposed of them, and also requiring that competent authorities review those statements, and verifiers conduct inspections;
b) requiring certification from product purchasers proving that a product will be used for a certain purpose, where this application is highly likely to lead to permanent storage (for instance as a building material).

Option a) would impose a very high burden on industry, competent authorities and verifiers and may provide a disincentive to purchase or handle CCU products. Due to the burden resulting from such measures, incentives would need to be provided which counterbalance the administrative costs. The level of compliance with regard to this measure may also otherwise be rather low.

Option b) may be more feasible than a) if the product purchaser is specialised (e.g. construction) and can prove that the product is consistently used for specific purposes. However, certain products can have multiple applications where the risk of emission is possible in some applications and not others.

Option 2.3: Setting boundaries for single installations or projects to receive exemptions

Option 2.3 could be considered to bypass issues related to tracking cross-sectoral carbon flows, with one possible alternative:

c) Only provide an exemption with regard to the surrendering of EUA where the CCU product is made and used in a bounded project (e.g. industrial symbiosis). This sub-option would only be possible in an altered ETS system where MRV is carried out at project-level rather than the installation-level (see option 1.1 above).

Option c) allows installations or groups of installations to be eligible; however, it is only feasible in a reformed ETS where project-based accounting is allowed. This option is therefore not currently possible; however, it should be explored further in the context of a mechanism such as presented in option 1 above.

Overall, the possible options a) to c) presented above show that it can be very costly and unpredictable to include CCU under the EU ETS. If the Commission decided to go further with this approach, a more in-depth impact assessment would be needed.

Option 2.4: Granting synthetic fuels to be used in ETS installations similar provisions as for biomass

For synthetic fuels an option could be to follow a similar route as the current provisions for biomass in the EU ETS. The treatment of biomass is explained in MRR (Monitoring Reporting and Regulation) Guidance Document #3. The EU ETS includes the same definition of biomass as in the Renewable Energy Directive (RED):

> 'Biomass' means the biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste; it includes bioliquids and biofuels.

The EU ETS applies a zero-rating for emissions from biomass. In the MRR Guidance document it states that this implies that within the EU ETS bioliquids and biofuels are only included if the sustainability criteria from the RED are met. RED II also introduces such sustainability criteria for biomass and biogas.

The calorific value of the biomass can be important with regard to determining the total emissions of an installation that partly uses biomass. In this case the guidance document describes specifically which methods can be used to determine the relative carbon content of the biomass used. These can be used in the monitoring and reporting from the installations.

A similar treatment could be envisaged for synthetic fuels. This implies that the user of synthetic fuels is capable of deducting the CO_2 emitted from using these fuels from their reported emissions. Biomass and synthetic fuels to need to be included with a zero-emission factor, as long as this is not required under the Renewable Energy Directive (see 3.3.6).

Using this option will lead to some regulatory challenges.

- CCU processes leading to synthetic feedstocks cannot be stimulated according to this route. That may lead to a preference in the market to deliver synthetic fuels. Therefore regulatory stimulation through this route may distort competition and not lead to cost-optimal carbon reduction.
- Stimulation of synthetic fuels through this route may result in double incentives if synthetic fuels are also supported by national governments implementing RED II. It would therefore be advisable that first research is performed on the (fiscal or financial) stimulation of synthetic fuels in Member States and to what extent such would interfere with the EU ETS.

- In most cases synthetic fuels produced by installations within the ETS will be used in transport, outside the ETS. In this case the climate benefit (e.g. the avoided fossil fuel) is to be attributed to the user of the fuel, as mentioned by Bardow and Green (2018) and in Box 6 above. This effectively means that carbon captured for synthetic fuels would have to be excluded from incentivisation under the ETS. Synthetic gas may also be used for, for example, heating purposes within ETS companies. As long as the climate benefit is only accounted for by the user of the synthetic fuel, the ETS rules can be consequently applied, avoiding double counting.
- As the electricity input needs to be from renewable resources in order for synthetic fuels to be climate beneficial, and as these renewable resources should ideally not be competing with electricity demand from other sources, it will be very difficult to determine the climate benefit of synthetic fuels. This would need to be considered in detail before the use of synthetic fuels by EU ETS firms could be granted emission reductions.
- The technology neutrality principle would also be violated if producers of synthetic fuels are granted emission credits or can report avoided CO_2 emissions compared to other products.

Option 2.5: Extending existing rules for waste gas transfer to CCU

Waste gases form another cross-sectoral transfer flow in the EU ETS. The treatment of waste gases is laid down in the Harmonised Allocation Rules (EC/278/2011) and Article 48 in the MRR. The interpretation of this law is exemplified in Guidance Document #8. This document defines waste gases as:

> gases which emerge from incomplete combustion or other chemical reaction in an EU-ETS installation and which comply with all of the following criteria:
> - Waste gases are not emitted without further combustion due to a significant content of incompletely oxidised carbon;
> - The calorific value of waste gases is high enough for the waste gas to burn without auxiliary fuel input, or to contribute significantly to the total energy input when mixed with fuels of higher calorific value;
> - The waste gas is produced as by-product of a production process.

Waste gas issues typically arise in the iron and steel industry, where high-carbon blast furnace gas is used to produce electricity or heat through combustion. This is a cross-sectoral flow of gases that becomes especially relevant when electricity production falls under an auctioning regime while the iron and steel industry receives free allowances (up to the benchmark). Waste gas issues may also arise in the chemicals industry and refineries.

Guidance Document #8 on the harmonised free allocation methodology for the EU-ETS post 2012 sets forth a routine for how allocation of allowances occurs in these situations, including the following two conditions:

- These waste gases are used to produce electricity and/or heat.
- These waste gases have a carbon content higher than natural gas. Only emissions which are additional to the emissions that would occur if natural gas was used are taken into account. The EU ETS assigns additional ETS credits (compared to natural gas) to either the producer or consumer of these waste gases:
  - Emission allowances are being allocated to the producer of the waste gas, in case the waste gas is produced within the boundaries of a product benchmark. This is the case in the iron and steel industry. The idea is that the iron and steel industry will pass (part of) the freely obtained allowances on to the electricity producers to compensate for the higher carbon content.
  - In case the waste gas occurs outside the boundaries of a product benchmark, the allowances are allocated to the consumer of the waste gas. Processes that

do not fall under a product benchmark are subject to a heat benchmark. Waste gases in this area can occur in the chemical industry.

The cross-sectoral flow of carbon related to use within products could follow a similar route where (free) emission allowances can be allocated to the producer of the captured CO_2 gases in the event that the CO_2-waste gas is produced within the boundaries of a product benchmark, while the allowances can be allocated to the consumer of the CO_2-waste gases if the producer of the CO_2-waste gas does not fall under a product benchmark. The consumer could then 'pay' free allowances to the producer of the waste gasses to offset the producer's additional investments to capture the CO_2.

This option results in some regulatory challenges:

- It may not always be clear if an installation falls under a product benchmark or not, and some installations may produce multiple products, of which some fall under a product benchmark and others not. Therefore, it will be complicated to allocate the CO_2 reduction in such case.
- The inclusion of CCU in this way would also have consequences for other pieces of legislation, such as benchmarks. When CCU is regarded as a means to lower emissions, it can be argued that this accelerates the technological progress reducing CO_2 emissions under the benchmarks. Furthermore, the inclusion of CCU would require a new calculation of the relevant benchmarks (as described in Box 3 above); however, this procedure has not been foreseen within the revised ETS Directive.
- This route would be stimulated if a predefined list were to be established of CCU technologies for which CO_2-gas transfers can become eligible as an emission avoidance technique. However, transfers of CO_2 captured by an installation within the ETS and transferred to installations or customers outside the EU ETS could potentially cause problems with regard to allocating free allowances.

Option 2.6: Applying a similar route as heat transfer in the current ETS

Finally, CCU and the cross-sectoral flows of carbon could be regulated in a similar way as the current heat transfer rules. Various cases of heat transfers are possible in the ETS under the Benchmarking Decision, and the allocation rules are explained in more detail in Guidance Document #6 on the 'harmonised free allocation methodology for the EU-ETS post 2012 Cross-Boundary Heat Flows Final'. Heat is eligible for free allocation up to the benchmark if two conditions are met:

- the producing or consuming installation is covered by the EU ETS;
- the heat is not produced by electric boilers.

The following four situations may now occur.

- Heat flow within one ETS installation. In this case the installation may choose whether it applies the product benchmark (e.g. paper) for the consumption of that heat, or the heat benchmark for the consumption of heat.
- Heat flows between two ETS installations. As a general rule, free allocation up to the benchmark is given to the consumer of the heat, which has to count this heat as a fuel input in its product benchmark.
- Heat flows from an ETS installation to a non-ETS installation (or entity). In this case, the free allowances are given to the heat producer. However, non-ETS units are supposed to be non-carbon leakage. Therefore, the carbon leakage factor does not

apply unless the heat exporter provides satisfactory evidence that it exports heat to a unit that is exposed to a significant risk of carbon leakage. It could, for example, be the case that the consumer is a non-ETS industry which falls under a NACE-4 classification that qualifies for free allowances under the EU ETS.

- Heat flows from a non-ETS entity towards an ETS installation. The consumption of heat produced outside the EU ETS is not eligible for free allocation (since the producer does not fall under the EU ETS).

Something which could thus be envisioned is introducing a 'carbon benchmark', for example based on LCA, against which the transfer of carbon to product use is evaluated. It goes beyond the scope of this study to exactly outline how that could be done.

The heat transfer framework would especially be relevant to considering transfers of CO_2 to non-ETS customers of CCU products. However, there are a few regulatory challenges with regard to this option:

- This option would require considerable new studies, for instance in defining the 'carbon benchmark' defined above. In such a study a few potential flows of carbon would have to be investigated in detail and the regulatory challenges for each of these options would have to be investigated. The inclusion of CCU in the MR/AV Regulation may have consequences for other pieces of legislation in the ETS, such as benchmarks. The Benchmarking Decision will be updated in view of free allocation rules update, including the benchmark values which reflect technological progress.
- If the MR/AV Regulation is to recognise CCU technologies as a way to reduce CO_2 emissions, this option may have to be incorporated in calculating the rate of technological progress applying to the benchmark values, as the verified emissions will be lower.
- The cross-boundary role of this option may imply a change in the ETS/ESR split, as indicated in Box 3 above.

Conclusion

To sum up, it is still difficult to design a system under the EU ETS in which the net CO_2 emission reduction of CCU processes can be calculated at a reasonable cost and without making the introduction of CCU into ETS/MRR/AVR regulations extremely cumbersome for operators, competent authorities and verifiers. Much of the design of new mechanisms which may be adapted to CCU remains to be agreed upon and rendered more operational under EU and UN auspices.

A particular reason for these difficulties is that the EU ETS uses installation-based rather than product- or project-based accounting, but the latter two are desirable when addressing CCU applications. We therefore recommend that the European Commission continues to explore the above options to include CCU in the framework of European greenhouse gas market mechanisms. The following problems should particularly be addressed, they are followed by recommendations.

- **Enable the ETS to account for avoided CO_2 emissions outside the boundaries of a single installation.**
  The ETS regulates installations and their emissions. Due to this design the LCA methodology used in Task 1.2 (which also considers emissions avoided outside of a producing installation) cannot be assumed under the current ETS system. A fundamental change to the ETS would be needed to accommodate the LCA approach

such as adopted in Task 1.2, which at present appears to be the best approach to assess avoided GHG emissions from CCU technologies.

- **Avoid double counting of emissions, consequently attributing the right incentives to installations.**
  Related to the problem above, the accounting of CO_2 emitted or avoided requires that the incentive system for exempting ETS installations from surrendering allowances takes into account the chain of products which CCU products enter so that CO_2 emissions avoided and emitted CO_2 are reported once and lead to one incentive.
- **Prevent unreported CO_2 emissions escaping the scope of the ETS ('internal carbon leakage').**
  Following the capture of CO_2 from an emitting process and subsequent transfer of carbon for use as a feedstock in CCU production processes, the resulting products could be used and disposed of so that emissions of CO_2 occur outside of the boundaries of the ETS. This has implications regarding which installation along a product chain should receive the exemption from surrendering ETS allowances. Monitoring methods are needed if one is to trace and properly account for emitted CO_2, or other guarantees to ensure that no carbon escapes from the ETS. Feasibility and costs are at issue when considering such additional measures.
- **Assess CCU processes individually to properly account for their environmental impacts.**
  Exemptions to the obligation to surrender emission allowances cannot be granted for installations to all CCU processes making the same product, as these may entail a range of production processes with high variation in process emissions. This means that each installation's production process must be verified to ensure that emissions are avoided.

In the short term we recommend only incentivising products which offer permanent storage applications (e.g. PCC for construction) with demonstrated climate mitigation benefits, thus complying with the CJEU preliminary ruling in the *Shaefer Kalk* case. This requires implementing option 2.1 (mapping possible applications of products) in combination with option 2.2. The European Commission should continue to address the design and feasibility of monitoring and verification methods for CCU among competent authorities of the Member States, verifiers, MRV experts, and industry. The goal should be the development of MRV methodologies and simplified LCA guidelines which are comprehensive in their approach to environmental impacts while still being affordable.

In the medium or long term the European Commission should explore project-based GHG emission accounting approaches under option 1 (and option 2.3(d)). Projects are ongoing which may provide a unified approach to monitoring GHG emissions from CCU which are consistent with existing emission trading systems. Options 2.4, 2.5 and 2.6 would also require further study should they be selected as possible options.

However, in view of the recognised limited mitigation potential and technology maturity challenges in terms of scalability, greenhouse gas accounting methodology, ensuring security of CO_2 sources in a decarbonisation pathway, and high energy needs (competing with increased demand for electrification from renewables), research should also continue in order to understand other pathways to incentivise the most climate-friendly of these technologies. These alternative mechanisms should therefore be assessed and implemented where they appear more advantageous.

3.4.3 Piecemeal approach

In this Section we build on the existing policy framework identified as relevant and beyond that offered by the EU ETS. The options may not be exclusive.

3.4.3.1 Products and labelling policy framework

The followings options are proposed to help climate beneficial CCU products penetrate conventional markets by creating a demand, and hence ensuring replacement of conventional products by CCU-based products.

Option 1: Introducing product-blending quotas

In this option quotas on products and chemicals would be introduced so that minimum amounts of CCU products would need to enter conventional product markets, similarly to the mechanism introduced by the RED and the FQD (see Sections 3.3.6 and 3.3.7).

Product-blending quotas could be particularly helpful in helping CCU products penetrate conventional markets=, possibly creating investment certainty with the knowledge that there is a demand for CCU products, and therefore facilitate technological development and scaling-up, progressively lowering production costs and making CCU products more competitive.

Before commencing a more detailed discussion of blending quotas it is very important to note that such mechanisms, if used on specific products, need to avoid technological bias, meaning that they should be carefully considered with regard to the range of solutions that exist or may become technically feasible and potentially preferable over CCU products. For instance, in the construction sector the reuse of building materials could be more beneficial than the use of CCU products. Product-blending quotas should therefore not make CCU products more competitive than the more beneficial alternative solutions.

Quotas may be applied to different actors in the value chain (such as producers, processors, or purchasers) depending on the market targeted and its dynamics, and in order to ensure that the incentives are properly addressed. The public sector (as purchaser) is potentially a better target for implementing quotas due to the higher concern for public benefit, and existing frameworks regarding green public procurement.

The quotas would be time-bound, meaning that targets for minimum shares of CCU products would be set. A system of guarantees of origin would help to show to final customers that a given share or quantity of the product purchased was produced from recycled CO_2.

The practical implications of this option were discussed during stakeholder consultations for the project and led to some identification of preferences for the option.

The potential success of quotas was identified as depending greatly on which markets the quotas are applied to. Quotas setting minimum shares for carbon-recycled products in EU products which are traded internationally and therefore compete with countries with lower standards risk being at a competitive disadvantage. By contrast, those products generally sourced within the EU and for internal consumption are less exposed. This applies to, for instance, concrete.

One of the key challenges for this option is the need for great caution when introducing such market instruments so as to avoid environmentally damaging policies, as have occurred in the past with biofuels. A detailed impact assessment would therefore be needed to further define the specific design and possible effects of this option.

Product quotas also need to be supported by additional rules and monitoring to ensure that there is no loophole and that the measures do not create market distortions. For instance, monitoring of the measures would be required to ensure that the quotas are not enforced for 'too long' or repealed 'too soon', i.e. after the measures have proven to be ineffective or before they have been proven to be effective.

More research (such as impact assessments) is needed in order to establish the feasibility, effectiveness and coherence of this option. In particular, research should address which products or sectors can be regulated using such quotas and whether sectoral policies would not conflict with the new mechanisms.

Option 2: Developing a voluntary labelling and certification scheme for carbon-recycled products

Labelling policy for CCU products, indicating an item whose production involved a CCU process at some point, is difficult to draft. This is not least due to the diversity of possible products and their characteristics of being an intermediate or an end product (Olfe-Kräutlein et al., 2016). The EU Ecolabel scheme could, in principle, apply to CCU products; however, the feasibility of this option could not be assessed based on existing knowledge, in particular as a barrier with regard to consumer preferences or in a lack of readiness to pay more for a 'green' product made with CO_2 cannot be foreseen today.[142] According to IEAGHG Technical Review 2018,[143] the potential benefits remain unclear. To date, CCU operators have preferred to take the option for self-certification.[144]

Despite the uncertainties in perspectives regarding labelling and multiple obstacles to be overcome in the further design and achievement of a certification for CCU products, governments, industry and associations should already begin to consider and, if necessary, prepare the development of regulations and certification options in co-operation with experts from the fields of environmental protection and certification in order to foster public acceptance.

3.4.3.2 Waste and circular economy policy framework

The analysis of the current legal setup concerning waste management has identified legal barriers for the marketing of CCU-based products. Most relevant is the absence of a harmonised application of the end-of-waste criteria by Member States for CCU-based products. In other words, Member States have different views on when a recycled waste stream ceases to be waste and becomes a product. Linked to this barrier is the issue of the presence of potential substances of concern in waste streams and consequently in CCU-based products which are recycled from these waste streams. The highlighted barriers might result in the limiting of markets for CCU-based products. Furthermore, from a long-term perspective, the safety and environmental soundness of CCU-based products should be guaranteed, to prevent risks for human health and the environment and to ensure acceptance by consumers. This Section will highlight various policy option to address the aforementioned issues.

<u>Options related to the Circular Economy Action Plan (CEAP)</u>

Option 3: Including CCU as part of CEAP objectives and strategies

[142] Hendriks, C., Noothout, P., Zakkour, P., & Cook, G. (2013). *Implications of the Reuse of Captured CO_2 for European Climate Action Policies*. Retrieved from Utrecht: http://www.scotproject.org/sites/default/files/Carbon%20Count,%20Ecofys%20(2013)%20Implications%20of%20the%20reuse%20of%20captured%20CO2%20-%20report.pdf

Jones, C. R., Olfe-Kräutlein, B., & Kaklamanou, D. (2016). Lay perceptions of carbon dioxide capture and utilisation technologies in the UK and Germany: a qualitative interview study.

[143] IEAGHG. (2018). Greenhouse Gas Emissions Accounting for Carbon Dioxide Capture and Utilisation (CCU) Technologies. 2018-TR01.

[144] See Subsection 7.3.

Envisaged changes to legislation and its application or interpretation, as highlighted in policy options below, will require political and policy momentum. Consequently, placing the issue of CCU products within a relevant policy discourse becomes important. If a specific policy strategy for CCU proves challenging, an intermediate option would be to further link CCU developments with other policy strategies under the CEAP, depending on the products resulting from CCU operations. For example, the EU strategy for Plastics in a Circular Economy already makes specific mention of using CO_2 as feedstock. As such, options to stimulate CCU for the production of plastics could be linked to actions taken as part of that strategy.

This option is here formulated generally and would need to be further explored in detail; however, it seems to require relatively small efforts to provide a 'soft' policy push for CCU in EU circular economy policy once their environmental benefits are proven in terms of resource efficiency. This option may provide more clarity to policy-makers, industry, researchers and consumers as to the contribution of CCU to the circular economy.

Options related to the Waste Framework Directive (the WFD)

When discussing the policy option for CO_2-based products under the legal framework for waste it should firstly be noted that, as part of the EU Circular Economy Package, a legislative proposal was put forward by the European Commission including legal amendments to the WFD and more specifically Articles 2, 5 and 6 thereof which are relevant to the current assessment.[145] A political agreement was reached in December 2017, which is very likely to result in final amendments to the WFD. Prior to the introduction and application of the amended WFD, it will be difficult to assess how the envisaged amendments will affect the status and obligations concerning CO_2-based products in practice. Therefore this Section will refer to the envisaged amendments to the WFD if their very wording provides sufficient ground to assume relevance for the current analysis.

Option 4: By-product status for input materials of CCU-based products

As highlighted under Section 3.3.13, input materials for CCU products could be classified as waste, which would lead to the application of the waste legal framework to CCU activity. Consequently, CCU activity will have to comply with the requirements of waste treatment operations. Furthermore, any product which derives from CCU activity will have to meet the criteria of Article 6 of the WFD in order to be considered a product. This could become a barrier, due to the varying application of the end-of-waste criteria of Article 6 of the WFD by Member States.

A first relevant option with regard to the definition of waste would be classifying the input materials for CO_2-derived products as by-products, as provided for in Article 5 of the WFD. The classification of input materials as by-products would mean that the Member States do not consider these materials to be waste. Subsequently, the CCU activity will only have to comply with the requirements of relevant product legislation.

According to this provision, a substance or object resulting from a production process the primary aim of which is not the production of that item may be regarded as not being waste referred to in point (1) of Article 3 but as being a by-product only if the following conditions are met:

> (a) further use of the substance or object is certain; (b) the substance or object can be used directly without any further processing other than normal industrial practice; (c) the substance or object is produced as an integral part

[145] Commission proposal for a Directive of the European Parliament and of the Council amending Directive 2008/98/EC on waste, 2015/0275 (COD), Brussels, 23 February 2018.

of a production process; and (d) further use is lawful, i.e. the substance or object fulfils all relevant product, environmental and health protection requirements for the specific use and will not lead to overall adverse environmental or human health impacts.

With regard to the criteria for by-product status, a first important requirement would be that the input materials for CO_2-derived products result from a production process the primary aim of which is not the production thereof. More specifically, the material for which the waste or non-waste question is relevant as part of the by-product assessment has to satisfy this requirement.

It is possible that satisfying criterion (d) will be challenging for producers of CO_2-derived products, as described in the case of Carbon8 in Section 3.3.18. As with criterion (c) and (d) of Article 6 on end-of-waste status, it will not be easy in all cases to identify the applicable product legislation or the potential risks of using the by-product. In this regard it is important to note that criterion (d) of Article 5 requires the *use* of the by-product to not lead to overall adverse environmental or human health impacts. Therefore the fact that input materials for CO_2-derived products posses hazardous characteristics, does not automatically lead to criterion (d) not being satisfied. However, the burden of proof regarding the absence of overall adverse environmental or human health impacts will rest on the producer of the CO_2-derived products.

The feasibility of affording by-product status to input materials of CCU-based products will depend on the specific aspects of the various CCU techniques and has to be assessed on a case-by-case basis. Such case-by-case assessments, which should be carried out or verified by the national competent authorities, may require substantial costs and capacity. An option in this regard would be the adopting of specific by-product criteria for CCU products' input materials,[146] as will be provided in the amendments of para. 3 of Article 5 of the WFD under the Circular Economy Package. However, it seems unlikely that Member States will dedicate efforts to adopting specific criteria for specific input materials which might change or become less relevant in the future.

Finally, issues raised in the literature regarding the varying application of end-of-waste criteria by Member States are likely to also apply to the application of the criteria for by-product status. Therefore this option is relevant in as far as the Member States which are concerned with the status of a CCU product apply the by-product criteria in a similar way. For CO_2-based products an option would be the adopting by the Commission of specific by-product criteria at the EU level, as currently provided for by Paragraph 2 of Article 5 of the WFD. However, it should be noted that the potential of this option is not certain. So far harmonised end-of-waste criteria have only been adopted for three material streams (see policy option 6). No harmonised by-product criteria have been adopted to date.

To sum up, the option of classifying the input materials for CO_2-derived products as by-products, as provided for in Article 5 of the WFD, might provide an alternative to the assessment of end-of-waste status by competent authorities of Member States. However, this option would only be relevant for production residues which are being used as input materials for CCU-based products. Furthermore, the challenge of varying application of end-of-waste criteria under Article 6 of the WFD could also exist for the application of the by-product criteria. Therefore the feasibility of this policy option should be assessed on a case-by-case basis for the different CCU techniques.

[146] For example, the Netherlands has adopted a regulation detailing specific by-product criteria for crude Glycerin originating from specific production processes. See: http://wetten.overheid.nl/BWBR0036424/2015-04-01

Option 5: Adopting harmonised end-of-waste criteria

With regard to the lack of harmonised application of end-of-waste criteria, the envisaged amendments of the WFD provide interesting options.[147] The amendment to Article 6 of the WFD provides for a more active role for the European Commission with regard to the monitoring of end-of-waste criteria at the Member State level and the potential development of Union-wide criteria. To this end, and where appropriate, the Commission should adopt implementing acts in order to establish detailed criteria for the uniform application of the conditions laid down in paragraph 1 to certain types of waste. According to the WFD proposal those implementing acts should be adopted in accordance with the examination procedure referred to in Article 39(2). Furthermore, the amendment states that when adopting acts in order to establish detailed criteria for the uniform application of end-of-waste criteria the Commission should take account of the relevant criteria established by the Member States and it should take as a starting point the most stringent and environmentally protective of those criteria.

Based on the above, a more active role for the Commission seems to be envisaged with regard to ensuring that more harmonised end-of-waste criteria are adopted. Within this context a policy option with regard to CO_2-based products would be the adoption of end-of-waste criteria at the EU level. This option is already possible under the current framework of the WFD, but might become more relevant after the amendment of Article 6 as described above.

Despite a potentially increased focus of the Commission on EU-level end-of-waste criteria, the drafting and adoption of such criteria remains a demanding option. So far, under the current system of adopting EU-level end-of-waste criteria, only three end-of-waste criteria have been developed (for iron, steel and aluminium scrap, glass cullet and copper scrap). The adopting of these criteria was preceded by technical proposals, developed by the Commission's joint research centre (the JRC).

Despite the competence to adopt end-of-waste criteria in the form of an implementing act, the required examination procedure as foreseen under the WFD proposal still provides for a system which requires the explicit consensus of the majority of the Member States for proposed end-of-waste criteria. The process for adopting end-of-waste criteria is described in the box below.

[147]Commission proposal for a Directive of the European Parliament and of the Council amending Directive 2008/98/EC on waste, 2015/0275 (COD), Brussels, 23 February 2018.

Box 8: Examination procedure for adopting end-of-waste criteria under the Waste Framework Directive

The examination procedure has been laid down in Articles 3 and 5 of Regulation (EU) 182/2011.[148] The procedure involves a system in which the European Commission first submits a proposal for an implementing act, based on a need as identified by a legally binding Union act, which is examined by a committee composed of representatives of the Member States. The committee then delivers its opinion on the proposed implementing act by way of a majority. If the opinion is positive, the implementing act is adopted. If the committee delivers a negative opinion, the Commission cannot adopt the draft implementing act. The option of submitting an amended proposal remains open. Where no opinion is delivered, the Commission may adopt the draft implementing act, except in the cases in which the basic act provides that the draft implementing act may not be adopted where no opinion is delivered. The proposed amendment of Article 39 of the WFD includes a paragraph which states that where the committee delivers no opinion, the Commission will not adopt the draft implementing act. The draft will also not be adopted if a simple majority of the component members of the committee opposes it.

Finally, as indicated under Section 3.3.13, the innovative nature of CO_2-based products might raise challenges with regard to meeting criteria (c) and/or (d) of Article 6 of the WFD, due to the potential lack of clarity about the applicable legal framework or the absence thereof. In this regard a suggestion would be an assessment of the interface between chemical, waste, and product legislation, with regard to the legal coverage of products resulting from CO_2-based products in the end-of-waste phase. A communication on the implementation of the circular economy package: options to address the interface between chemicals, products and waste legislation was published in January 2018.[149] Especially relevant is the focus of the chemical, product and waste legislation efforts with regard to the presence of substances of concern in recycled materials and, among other issues, the role of chemical, product and waste legislation. Specific actions with regard to CO_2-based products and the potential presence of substances of concern could be linked to this more general policy context.

To sum up, the adopting of harmonised end-of-waste criteria for specific CCU-based products would be the most direct solution for the varying application of the end-of-waste criteria of Article 6 of the WFD by Member States. A policy momentum seems to exist for increased harmonisation of end-of-waste criteria at the EU level, based on the proposed amendments of the WFD as part of the Circular Economy Package. However, the feasibility of this option remains uncertain, as previous attempts to harmonise end-of-waste criteria for other material streams have not been expeditive.

Option 6: Introducing requirements for marketing of CCU goods and defining end-of-waste criteria for secondary raw materials in that context

Another option could be to introduce requirements for safety and environmental soundness of CCU-based products and define or apply end-of-waste criteria for CCU-based products in that context. If product regulations can provide sufficient guarantees for safety and environmental soundness, the products satisfying the requirements should be considered safe to be placed on the internal market.

[148] Regulation (EU) 182/2011 of the European Parliament and of the Council of 16 February 2011 laying down the rules and general principles concerning mechanisms for control by Member States of the Commission's exercise of implementing powers (OJ L 55, 28.2.2011, p. 13).

[149] European Commission, communication on the implementation of the circular economy package: options to address the interface between chemical, product and waste legislation, COM(2018) 32 final, Strasbourg, 16 January 2018.

An interesting way of linking end-of-waste criteria to products regulations can be found in the Commission's proposal for a Regulation laying down rules on the making available on the market of CE-marked fertilising products.[150] Article 18 of the proposed Regulation states:

> A CE marked fertilising product that has undergone a recovery operation and complies with the requirements laid down in this Regulation shall be considered to comply with the conditions laid down in Article 6(1) of Directive 2008/98/EC and shall, therefore, be considered as having ceased to be waste.

A policy option for CO_2-based products would thus be to include a similar link in relevant product legislation. However, such an option would require very specific product legislation for all CO_2-based products. Furthermore, if relevant product legislation does exist for all products, it might be necessary to amend it to include specific requirements and standards relating to specific waste-related risks of CO_2-based products.

A more recent type of EU product regulations, referred to as the 'new approach',[151] could provide a more flexible way of including specific requirements and standards for recycled products. Under the new approach, a formal EU regulation will lay down the essential requirements for a product. Producers will have to prove conformity with these essential standards in order to be allowed to place their product on the single market. The most common way for producers to prove conformity is by meeting specific standards which are established by European Standardisation Organisations (CEN, CENELEC and ETSI). Such standards are often highly technical and tailored to specific product groups. In general, the development of such standards requires less time than the legislative and political process of amending EU legislation. Therefore, the adopting of standards for CO_2 based products and linking such standards to end-of-waste criteria could provide a more dynamic approach.

To sum up, the lack of harmonised application of the end-of-waste criteria of Article 6 of the WFD could partly be caused by the absence of clear and adequate product regulations or standards which can function as a guarantee against risks for human health and the environment. Current developments regarding the linkage between waste and product legislation provide an interesting perspective. Product regulations which sufficiently take into account potential risks stemming from CCU-based products could contribute towards a harmonised application of the end-of-waste criteria by Member States. Furthermore, newly adopted or adapted legal standards could help secure acceptance by buyers and the public. However, CCU-based products will continue to have to comply with the standards.

As a final note, and as discussed under Section 3.3.13, the current criterion (a) under Article 6 of the WFD requires that a substance or object is commonly used for specific purposes. The envisaged amendment of Article 6 of the WFD includes the replacement of this criterion with *'the substance or object is to be used for specific purposes'*. This new formulation is more innovation-neutral and decreases the possibility that Member State authorities consider criterion (a) of Article 6 of the WFD not satisfied in the case of new products, such as CCU operations.

3.4.3.3 Environmental pollution policy framework

Option 7: Identifying CCU as Best Available Techniques or Emerging Techniques

A policy option within the context of the IED would be the inclusion of CCU techniques as either 'best available technique' ('BAT') or 'emerging technique' in existing and/or future BAT reference documents (BREFs) for various industries regulated by the IED. As an important reference for

[150] Commission proposal for a Regulation on the making available on the market of CE marked fertilising products and amending Regulations (EC) 1069/2009 and (EC) 1107/2009, COM(2016) 157 final, Brussels, 17 March 2016

[151] https://www.cen.eu/work/supportLegislation/Directives/Pages/default.aspx

national authorities when issuing permits for IED facilities, BATs have the potential to stimulate the adopting by major industries of specific practices, such as CCU techniques. Furthermore, as BATs and emerging techniques in BREFS indicate the general development of environmental mitigation techniques in industry sectors, the inclusion of specific CCU techniques may function as an incentive for undertakings to start investing in techniques which are likely to become common or even obligatory in the future.

A preliminary analysis has not identified any CCU techniques in the existing BREFs. This implies that CCU techniques are currently not taken into consideration as tools to meet the emission limit values until the technologies are included as BAT. According to Recital 13 to the IED, the Commission should aim to update BREFs no less often than every eight years, which makes it possible for CCU techniques to be included at a later point in time. However, for a field of rapid technology development every eight years may be a long period, potentially leading to delays in taking advantage of promising technology.

In order to include CCU techniques as BAT in BREFs it should be assessed to what extent CCU techniques meet the definition of BAT. Subsequently, it needs to be assessed whether CCU techniques could be included as more obligatory 'BAT conclusions' in relevant 'BREFs' to ensure their use by a relevant IED-regulated industry. Alternatively, CCU techniques could be included in BREFs as a general BAT or an 'emerging technique', in which case the BAT criteria do not have to be satisfied yet.

Based on the analysis in Section 3.3.14, three distinct 'levels' of best available techniques under the BREFs can be identified, with different implications for the competent permitting authorities for IED facilities:

- BAT: persuasive reference for permit conditions.
- BAT conclusions: BAT, which is an obligatory reference for permit conditions.
- Emerging technique: to be taken into consideration by authorities and IED facility operators.

With regard to identifying a CCU technique as a BAT, the specific CCU technique has to be evaluated on the basis of the definition of a BAT and its requirements. For such an evaluation the criteria for determining best available techniques under Annex III of the IED provide indications and will therefore be taken into account in the analysis below.

Bearing in mind the assessment of existing CCU techniques under Chapter 2, the requirements for 'best' and 'available' are likely to require thorough assessment. The following two parts will provide a preliminary assessment of these two elements.

<u>The requirements for 'available technique'</u>

As described under Section 3.3.14, 'available techniques' means those developed on a scale which allows introduction in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator. In this regard, the criteria of Annex III to the IED may be relevant. These criteria require:

- that comparable processes, facilities or methods of operation have been tried with success on an industrial scale;
- that the commissioning dates for new or existing installations and the length of time needed to introduce the CCU technique are taken into account.

It should also be noted that the current mention of carbon capture (CC) and carbon capture and storage (CCS) under existing BREFs are categorised as emerging techniques.[152] Therefore it might be difficult to argue that carbon capture followed by use is to be considered a BAT. The current categorisation of CC and CCS as emerging techniques also makes the categorisation of CCU as BAT conclusion unlikely at the moment, as the techniques are not considered as sufficiently developed to be 'available'. Furthermore, the element of carbon use as part of CCU techniques might be challenging to establish as a mandatory element of permits for certain IED facilities, due to a current lack of economic feasibility. However, the economic feasibility of specific CCU techniques should be assessed on a case-by-case basis.

Due to the novelty of CCU techniques, the most likely option from the 'availability' perspective would currently be their inclusion in relevant BREFs as emerging techniques. By identifying CCU techniques as emerging techniques both competent authorities and IED facility operators might become more aware of the option of, respectively, requiring or adopting such techniques in the future, or even the obligation to require or adopt such, if a CCU technique develops to the extent that it is considered to be a BAT or BAT conclusion. Furthermore, Article 27 of the IED already provides a soft obligation for Member States to apply emerging techniques where appropriate. The fact that CCS and CC techniques are already listed as emerging techniques under certain BREFs may support the argument for the inclusion of CCU under the same category.

The costs involved in including CCU techniques as emerging techniques under certain BREFs would be limited, due to the non-obligatory nature of this classification. However, the technical feasibility of including CCU techniques as emerging techniques under certain BREFs should be assessed based on the relevant existing or newly drafted BREF, to make sure that the future application of the envisaged CCU technique is realistic within a specific sector.

<u>The requirement for 'best technique'</u>

As described in Section 3.3.14, 'best' means most effective in achieving a high general level of protection of the environment as a whole. However, for certain CCU techniques it might be challenging to assess the overall environmental benefits.

More specifically, some of the criteria provided in Annex III to the IED are hard for certain CCU techniques to meet. One example may be found in No 9 of Annex III on *'the consumption and nature of raw materials (including water) used in the process and energy efficiency'.* Given that several of the CCU techniques are energy intensive, this requirement would potentially be hard to meet. For synthetic fuels in particular this paragraph would potentially pose a hurdle for classification as BAT, if produced with DAC and being tied directly to the renewable energy producer. Furthermore, the requirement under No 10 on *'the need to prevent or reduce to a minimum the overall impact of the emissions on the environment and the risks to it'* may be difficult to assess, given that limited information is available on the LCA and environmental impacts of many of the techniques.

Also worth noting is criterion No 2, the requirement to use *'less hazardous substances'.* CCU techniques, which use hazardous substances or waste as input materials may not meet this requirement. However, criterion No 3 requires the taking into consideration of *'the furthering of recovery and recycling of substances generated and used in the process and of waste, where appropriate*'. The balance between criteria No 2 and 3 can be linked to the discussion on the balance between increased recycling under a Circular Economy and the Union's aim of non-toxic

[152] These BREF documents are: Iron and Steel Production, Large Combustion Plants, Refining and Mineral Oil and Gas

material streams, as described under Section 3.3.13 and the communication on the interface between chemical, product and waste legislation.[153]

To sum up, due to their novelty and lack of information regarding overall environmental impact, CCU techniques are not likely to be listed as BAT conclusions or general BAT in BREFs. The listing of CCU techniques under BREFs as emerging techniques seems more feasible. However, such a listing should be based on a case-by-case assessment of specific CCU techniques. By identifying CCU techniques as emerging techniques an incentive may be created for competent authorities to take these techniques into account when establishing permit conditions. For IED facility operators the listing of CCU techniques as emerging technologies could function as an indication of future developments and might function as an incentive for investment in these techniques.

3.4.4 New CCU policy

EU policy concerning CCU tends to be spread across different policy frameworks, a logical consequence of the different sectors and processes encompassed by the term. It would be interesting to consider creating a new policy which would approach CCU in a single policy document in order to provide clarity.

The type of policy document which could embody CCU policy has been reviewed with the European Commission and with stakeholders. These discussions led to the conclusion that new legislation in the form of a Directive or Regulation would not be needed, as the measures embedded in other policy frameworks are sufficient.

Instead, a ‘soft’ policy approach, such as a CCU communication, would be preferred. The communication would present the Commission’s work and position regarding CCU, clarifying the policy objectives and applicable framework for CCU in a single document, and providing clarity for the entire sector and across government bodies. This option is explored further in Option 1 below.

Option 1: A Publishing a European Commission communication on CCU

As discussed in Chapter 2 (Task 1), the public discourse around CCU currently lacks a clear framing of what this group of technologies entails and what are their positive and negative environmental and climate mitigation effects. Furthermore, there is a confusion between CCS and CCU. Finally, the positions and objectives of the EU and national regulators with regard to CCU are diverse, and the EU’s policy as a whole lacks a clear direction. The EU policy framework which can potentially affect CCU is partly defined in this study, but more current and future policies will likely be linked to the development of CCU, considering the diversity of technologies.

A Commission communication on CCU is proposed to help address these issues. Stakeholder consultation for this study enable the purpose of such a publication to be identified.

First of all, the communication could offer a clear definition of CCU and differentiate it from CCS.[154]

Secondly, the diversity of CCU technologies would be identified in the publication presenting the different industries and sectors where CCU is found, and provide a brief overview of the state of

[153] European Commission, communication on the implementation of the circular economy package: options to address the interface between chemical, product and waste legislation, COM(2018) 32 final, Strasbourg, 16 January 2018

[154] Such a definition is offered in introduction to this study and therefore not repeated here.

play of the technologies at present and for the foreseeable future. This would need to include a brief review of known environmental and climate impacts, based on established science, and also market and societal issues, including risks and opportunities with regard to CCU deployment.

Thirdly, from this understanding of CCU a link to relevant EU policy frameworks could be made to clarify what legislation applies to CCU, and also which policy objectives CCU can potentially contribute to and to what extent. 'CCU-specific' could also be set out in this publication, including quantitative targets for the reuse of CO_2, or the share of products made from recycled carbon (see also Section 3.4.3.2 on product-blending quotas). The publication would also provide an overview of existing incentive mechanisms under different policy instruments, including legislation and financing programmes and instruments. The eligibility and requirements for receiving support should be clearly stated, such as the need to prove environmental benefits (using a standard or recognised LCA methodology), and the need to follow established GHG accounting methodologies and avoid double counting of emissions under different EU policies.

Finally, the communication would initiate a collaborative process across Commission Directorate-Generals and could potentially involve other stakeholders to agree on its contents. It would also serve as a reference document for future EU policy initiatives.

Obstacles to the drafting of such a document include the fact that there are still gaps in and disagreements with regard to knowledge of the possible impacts of CCU technologies; however, we suggest that basic information needed to suit this document's purpose is becoming more and more available, as presented in this Report.

To sum up, the diversity of CCU technologies and the related policy frameworks have created confusion in the discourse regarding CCU. It is highly relevant to consider the publication of a single document providing clarity to the debate. Consequently, we recommend taking this option.

3.4.5 A nothing-new policy

Under this approach no additional policy would be enacted other than the baseline framework detailed in Section 3.4. This option makes sense from a climate mitigation perspective. In the present energetic context, where renewables are not yet sufficiently available, CCU technologies have little promise of offering significant GHG emission reductions, due to their high energy intensity. For this reason the costs of adapting the EU regulatory framework to accommodate CCU should be weighed against benefits offered by such technologies.

The only change in policy regards financing programmes, where recommendations for financing are adopted. Specific options are assessed.

Option 1: Not including CCU under the EU ETS in any near future

The assessment of the current state of the EU ETS as regards CCU in Section 3.3.3 has concluded that the current system recognises CCU technologies as possible 'breakthrough innovation' and that these technologies are eligible for funding under the Innovation Fund, provided that CCU projects deliver net reduction in emissions and ensure the avoidance or permanent storage of CO_2. The system is considered to not fully accommodate the type of climate mitigation benefits which CCU processes can potentially offer, due to the difference between the accounting systems for an LCA approach on the one hand and MRV methodology on the other. It is also thought to be premature to consider changing the system, in view of the confirmed uncertainty regarding the environmental benefits and climate change mitigation potential of the CCU technologies, and the options considered in Section 3.4.2 are exploratory.

Analysis of policy options for reforming the system (see Section 3.4.2) have not led to the identification of robust solutions, but have led to the conclusion that the costs of the revisions may be very high and involve possible loopholes, in particular when compared to the potential benefits from the technologies. In fact, the development of an accounting system for cross-sectoral transfers of carbon is still ongoing,[155] and discussions between experts have not concluded with regard to the correct incentivisation methodology for exempting ETS installations from surrendering EU allowances for avoided emissions or when carbon is stored permanently.

Consequently, one option would be to not reform the ETS to try to accommodate CCU in any near future, so as to avoid any unforeseen consequences of an ETS incentivisation approach before a better consensus can be reached regarding the technologies' positive impacts, and a least burdensome approach can be found with regard to establishing an appropriate incentivisation system which avoids internal carbon leakage, double incentives, and technological lock-in for the most environmentally impacting technologies.

A key consequence of not exempting CCU projects from surrendering allowances (or granting them carbon credits) is that installations will continue to have to report emissions from their installations where those do not actually occur, and therefore they will need to purchase allowances. On the other hand, installations would have additional revenues from the marketing of low emission products, which may benefit from markets created through other legislation (such as RED II with synthetic fuels). This option should therefore be balanced with other options in order to provide targeted incentives for technologies which show potential for climate mitigation and contribution to a more efficient use of resources (the circular economy). Such technologies have been identified in Task 1 and options for support presented above and below.

To sum up, there are good reasons for not including CCU under the ETS in any near future, except for the implementation of the preliminary ruling of the CJUE. First of all, studies suggest that CCU may only have a very small role in climate mitigation.[156] Research on CCU faces significant methodological gaps concerning GHG emission accounting for CCU. The EU should, however, continue exploring ETS and non-ETS policy options for supporting CCU technologies with a high resource efficiency and climate mitigation potential.

Option 2: Continuing to support scaling up of CCU technologies via EU financing

As detailed in Section 2.2 (Task 1.1) and 3.3 (Task 2.1), the financing of CCU is already possible under existing EU financing programmes and instruments. It is therefore not necessary to imagine the creation of a specific fund for financing CCU. However, the above analysis has highlighted gaps in the funding of certain types of projects, mainly mineralisation. In this Section we provide policy recommendations regarding how to best focus funding of CCU projects in the future.

As stated in Task 1.1, EU financing should support CCU projects with climate mitigation potential on the basis of LCA, in particular those projects where such potential is limited to replacing conventional production processes normally involving a fossil- or bio-based feedstock. This is already envisaged as part of the Horizon 2020 application and selection process, and should be a criterion under the new Innovation Fund (discussed in further detail in Section 2.3.3).

[155] See, for instance, IEAGHG. (2018). Greenhouse Gas Emissions Accounting for Carbon Dioxide Capture and Utilisation (CCU) Technologies. 2018-TR01.

[156] Mac Dowell, N., Fennel, P.S., Shah, N. & Maltland, G.C. (2017). The role of CO_2 capture and utilisation in mitigating climate change. Nature, April 2017, vol. 7, pp. 243–248.

Previous literature has suggested supporting the creation of European shared modular pilot plant and verification centres.[157] Such plants would make possible the piloting of different CCU technologies and could support research and the identification and understanding of carbon-efficient CCU processes.

EU programmes for regional development and cohesion (ERDF and CF) and for strategic investments should also prepare for the scaling-up of technologies which will become commercially viable in the future.

By ensuring a balanced selection of CCU technologies to finance across the product clusters identified (fuels, polymers chemicals and minerals), different CCU applications would receive equal treatment.

In conclusion, while EU funds exist or will become active in the next few years (e.g. 2020 for the Innovation Fund), the use of these funds must be more widely spread across different technologies so as to accelerate the spread of circular resource patterns and climate mitigation in different industrial sectors of the economy.

3.5 Task 2.3: Assessing policy options

In this last Section of Task 2 we discuss each of the four broad policy approaches for which options have been defined in Section 3.4. Discussed in particular are the possible contributions of the measures to large-scale CCU deployment and possible long-term economic, social and environmental effects. As these effects have been discussed in detail in Section 2.4 (Task 1.3) above, we have not repeated statements already made if they are not specific to the policy measure discussed. Where relevant, we have focused on the clusters of CCU technologies concerned by the options and their impacts (polymers, fuels and minerals).[158]

3.5.1 EU ETS approach

Implementing the CJEU's preliminary ruling concerning the *Schaefer Kalk* case has led the European Commission to recognise the capture of CO_2 as an avoided emission in the case of CO_2 chemically bound in PCC as a stable product. If not implemented with great caution, this can pose risks of **internal carbon leakage** and **double counting** in the European greenhouse gas accounting system, leading to improper incentivisation of installations whose captured carbon is merely re-emitted elsewhere.

The prospect of introducing CCU into the ETS raises the question of whether ETS incentives should be provided where other mechanisms already exist or are planned. In particular, Carbon Counts and Ecofys (2013)[159] warn against the **combined use of push and pull mechanisms** such as financial support and ETS incentives or other market pulls (blending quotas, etc), which can create **market distortions**.[160]

Combined **incentives for CCU fuels**, as provided under the RED II and FQD blending quotas and ETS incentives (both pull mechanisms) are recommended by Bardow and Green (2018) in light of the high operating costs for the production of CCU fuels and considering that they tend

[157] Wilson et al. (2016). A Strategic European Research and Innovation Agenda for Smart CO_2 Transformation in Europe. SCOT Project,. p. 4.

[158] Specific statements concerning chemicals could not be made at this stage and could be explored in further research.

[159] Ecofys and Carbon Counts. (2013). Implications of the Reuse of Captured CO_2 for European Climate Action Policies. By order of European Commission DG Climate Action.

[160] Ecofys and Carbon Counts. (2013). Implications of the Reuse of Captured CO_2 for European Climate Action Policies. By order of European Commission DG Climate Action. pp. 71–72.

to offer the largest potential market volume (see also Task 1). The risk of too much incentive for CCU fuels includes **fostering a market preference for the use of platform chemicals, such as methane, for the production of fuels over polymers**. Finally, and as warned about in Box 6 above, when dealing with fuels, the risk of double counting emissions avoided by the producer and the user of the fuel must be avoided.

In view of the risk of double counting, **products potentially offering permanent storage** under specific applications should be incentivised using option(s) 2.1, 2.2 and/or 2.3. As a caveat, these options require the mapping of all possible product applications which lead to permanent storage, or possibly only the main known applications. This may include, for example, products originating from mineralisation processes and used in **construction**. These options should **steer away from adopting an exclusively product-based approach** diverging from the installation-based approach of the ETS, as that may have unpredictable consequences for the integrity of the system. This means that **LCA analysis of specific CCU processes would still be needed** to establish the GHG emission mitigation potential, leaving as a burden for installation operators the providing of proof with regard to the emissions avoided due their processes. Although it appears necessary, this requirement has been criticised by stakeholders as being potentially prohibitively expensive. A simplified LCA methodology would be needed to deal with this problem.

As a list of products can hardly be drawn without loopholes, as mentioned above, **monitoring and verification procedures for tracking CCU products** as they leave an installation and enter another, or become used in a non-ETS sector, would be necessary. However, the **costs of implementing such procedures are likely to be very high,** as underlined by options 2.1 to 2.3. Stakeholders have in particular pointed to the legal and practical difficulty, and the significant cost, for competent authorities and verifiers to conduct checks in installations which are not part of the ETS scheme or in relation to CCU products originating from a producing installation.

Furthermore, a push for CCU products to be used where they offer permanent storage would possibly occur **at the expense of other product applications** (refer, for example, to Box 2 presenting the possible applications for precipitated calcium carbonate). This solution is thus seen as a short-term response to the necessary implementation of the CJEU's preliminary ruling and would not immediately accommodate all technology clusters. **For applications which do not promise permanent storage other non-ETS measures should be pursued**. For instance (and as mentioned above), fuels of non-biological origin have now been introduced into RED II to count towards Member States' renewable energy targets and are incentivised via fuel-blending quotas in the transport sector. Ensuring that the RED II mechanism works well means avoiding those CCU fuels receiving too much incentive, such as double counting in different sectors,[161] or pushing for CCU fuels over low-carbon alternatives where they are becoming available, such as hydrogen fuel-cell transport or electric mobility for road vehicles compared to aviation.[162]

One long-term option of reforming the ETS points towards the **development of project-based GHG accounting mechanisms for CCU**, as presented in options 1 and 2.3(d). On the positive side, such mechanisms are already given some **basis under the UNFCCC CDM and the ETS**. However, the cost of creating a mechanism for project-based accounting is unknown, but likely to be high, as, yet again, **process-specific (comparative) LCA methodologies would need to be developed** in order to account for GHG emissions in the CCU process which can then be applied by projects. **Developing reference scenarios** are, for example, an important issue with regard to developing such methodologies. This would reflect the UNFCCC procedure for

[161] Christensen, A. & Petrenko, C. (2017). CO_2-Based Synthetic Fuel: Assessment of Potential European Capacity and Environmental Performance.

[162] Transport & Environment. (2017). Electrofuels – what role in EU transport decarbonisation?

developing 'approved methodologies', as presented in Section 3.4.2.3. Options 1 and 2.3(d) could also lead to important changes to mechanisms of the ETS, with unpredictable consequences. However, if the mechanism is sufficiently robust, **that could encourage environmentally beneficial industrial symbiosis approaches** by offering a carbon market incentive to projects using CCU processes in an industrial symbiosis set-up. Other forms of support can also be provided to encourage industrial symbiosis, as described further below.

Option 2.4 only incentivises CCU fuels, breaching the principle of technology neutrality and leading to a preference for CCU fuels to be produced from platform chemicals such as methane. This option would also lead to double incentives, as RED II is now expected to create a market pull for CCU fuels. These issues have been discussed above.

Option 2.5 results in difficulties establishing whether installations fall under a specific product benchmark which would attribute the allowances to either the producer or the consumer of the waste gas. Furthermore, this option would have consequences for other legislation, including the Benchmarking Decision. Finally, this option requires the drawing up of a list of CCU technologies leading to waste gas transfers which are eligible for reporting avoided emissions and receiving incentives.

Option 2.6 requires considerable study with regard to defining a 'carbon benchmark', but could be explored further.

As a general comment, it has been noted that the inclusion of CCU under the ETS is likely to lead to the need to adjust the emission targets set under the ETS and the ESR, as emissions would be allowed to move across sectors.

To sum up, all of the options under the ETS approach appear to either be costly or require important assessment of their legal and economic consequences. Furthermore, given the relatively limited climate mitigation potential of CCU technologies and their high operating costs, the costs of implementing the options defined in this study seem to outweigh the benefits. Further studies should be conducted to refine their design and mitigate the risks and costs; meanwhile other approaches should be pursued.

3.5.2 A piecemeal approach

The new policy measures contained in a piecemeal approach could potentially create a demand for CCU products; however, more research by product market cluster is needed.

As discussed in option 1, **product-blending quotas** could not be applied to all CCU products and analysis should be performed to establish to which product markets the measure would be most applicable. The option must be carefully designed so as to avoid putting EU producers at a disadvantage compared to international competition. Furthermore, the timing of such policies is essential: they should not be introduced or repealed inconsistently with the current stage of market development. Until more research has been conducted it is difficult to estimate the potential effects of this measure.

It is also uncertain whether **labelling policy** mentioned in option 2 would be effective in encouraging the consumption of CCU products if CO_2 reuse is not valued by a public willing to pay a price premium for demonstrated environmental benefits. The success of labelling is also likely to depend on the given product market. Further studies should be conducted.

Section 3.4.3.2 showed that evolution of the legal framework for waste and circular economy could benefit CCU, and make CCU a more visible approach for contributing to the circular economy.

Option 3, **including CCU as part of CEAP objectives**, may be a small effort and provide more clarity to policy-makers, industry, researchers and consumers with regard to the contribution of CCU to the circular economy. From a climate-mitigation perspective, the circular economy only makes sense if greenhouse gas emissions are avoided, reinforcing the need for LCA of CCU processes which reuse CO_2.

The **definition of by-product criteria** mentioned in option 4 needs to be agreed on following product-specific assessments carried out or verified by national competent authorities. However, the challenge of varying application of end-of-waste criteria under Article 6 of the WFD could also exist with regard to the application of the by-product criteria.

The **adopting of harmonised end-of-waste criteria**, as proposed in option 5, is a complex decision-making process which could require experts and competent authorities to expend time and resources; however, provided that an agreement can be reached, this option could support products which have faced difficulties with regard to placing CCU products on other European markets.

Product regulations, as described in option 6, could support the adopting of harmonised end-of-waste criteria by functioning as a guarantee against risks for human health and the environment with regard to products which could pose such risks. These regulations would set standard product safety requirements and potentially increase the acceptance thereof by buyers and the public, provided that the CCU products continue to comply with the standards.

If options 4 or 5 and option 6 are achieved in, for example, the construction aggregates sector (thereby supporting the case of companies such as Carbon8), existing commercial CCU **mineralisation products could receive a significant push** to be produced and sold across EU Member States. It has not been possible in this study to procure LCA results for mineralisation products, therefore the climate mitigation potential of these options cannot be assessed herein.

As a general comment, climate mitigation from carbon reuse can occur not only when CO_2 is captured and reused, thereby replacing fossil feedstocks, but also as carbon-based materials (construction materials, polymers, etc) are recycled, avoiding the need for extraction of new materials. By reducing the dependency on fossil feedstocks the **EU could reduce its dependency on the importing of fossil resources**.

3.5.3 New CCU policy

The option of issuing a **communication** on CCU offers important benefits for clarifying, at relatively low cost, what CCU is and how it is approached in the EU. The document could have relevant policy impacts by creating a common understanding for policy-makers, industry and the public. That could in turn lead to **better policy discussions**, which are currently hampered by lack of clarity about definition and potential mitigation impact of CCU. We hope that this Report is a useful contribution to that clarification.

3.5.4 A nothing-new policy

Under this approach we considered not seeking to include CCU in the EU ETS and pursuing financing of CCU projects under existing EU programmes.

There are good arguments to suggest that **not including CCU the ETS in the short-term is desirable**, given the uncertainty regarding the environmental benefits and climate change mitigation potential of CCU technologies, and may not result in significant problems, given that CCU-based production capacity is likely to remain marginal in the next ten years (see also Task 1.3).[163]

[163] Bazzanella, A.M. & Ausfelder, F. (2017). Low carbon energy and feedstock for the European chemical industry. Frankfurt am Main.

However, some support is due to help the development and subsequent deployment of CCU technologies. This support will be available in the form of EU financing across all stages of technology development and implementation, and should cover all CCU product clusters.

As Section 2.4 (Task 1.3) suggests, it is crucial that **EU financing policy should aim at funding CCU technologies which have high technical and economic feasibility, low environmental impact, and a sizeable deployment potential in the long term**. Overlooking such parameters could lead to mismanagement of public funds and economic losses.

Furthermore, the need for CCU processes to use renewable energy in order to be environmentally beneficial means that new CCU projects could lead to the **deployment of new and additional renewable energy power generation capacity**. This is particularly made possible by harnessing **synergies across EU financing programmes** to finance different parts of a project, as discussed in Section 2.2.4. **New energy capacity could be funded in conjunction with new CCU projects**.

Due to their high energy needs, CCU processes for fuel production should not take up renewable energy capacity, due to their very **inefficient energy conversion** from renewable electricity. The large-scale deployment of CCU fuel production capacity would need to be accompanied by **large-scale renewable energy deployment**. The best-case scenario for the environmentally rational production of CCU fuels is for their use as energy storage materials when renewable energy would otherwise be curtailed, and therefore lost if not converted. Using solely curtailed renewable electricity has, however, been highlighted by industry and European Commission stakeholders as financially unsustainable for CCU fuel production plants. Furthermore, in the longer term, energy curtailment may become less of a problem when **smart grids and efficient energy distribution** become more available.

Carbon-based fuels from CCU have the advantage of being **'drop-in' fuels**, meaning that they may be used directly using existing infrastructure (fuelling stations and vehicles). This advantage can also be an issue. The choice of which projects to finance is crucial in order to **avoid path dependency, particularly in the transport and power generation sectors**. As CCU fuels have been an important recipient of EU funding, decision-makers should prefer projects which **target the production of fuel in sectors where other, lower-impact fuels are less likely to compete**. This includes, for example, aviation. By contrast, a large-scale deployment of CCU fuel production and utilisation in road vehicles would slow down the development of **electrification** and **hydrogen technologies**, which also do not cause harmful effects on humans from tailpipe emissions compared to fossil fuels (and, to a lesser extent, CCU fuels).[164]

In European financing programmes funding for research and development is sometimes provided to cross-sector projects which **foster industrial symbiosis**, fostering synergy effects and more efficient use of resources. Support for research and development could furthermore contribute to **making the EU a leader with regard to CCU technologies**.

Finally, in the event that adequate funding is provided to a diverse portfolio of projects, Europe could become a leader with regard to CCU technology and producing carbon-recycled products. That could lead to modernisation effects and become an important economic competitive advantage with regard to the exporting of European expertise and products.

[164] Diesel-type CCU fuels tend to emit less NO_x and soot. Source: Bardow and Green, 2018.

3.6 Summary and conclusions of Task 2

The aim of Task 2 of this study was to assess the regulatory framework for CCU technologies identified as promising in Task 1 in order to identify issues between the technologies and legislation posing barriers to CCU development, or whether technologies need to change in order to become compliant. Issues related to the development of the technologies and identified in Task 1.3 and in the regulatory assessment were addressed with possible policy options. These options were further assessed with regards to their feasibility and potential impacts, where such were possible to estimate, or led to suggestions for further research.

The **regulatory assessment** in Task 2.1 screened more than 25 pieces of legislation, of which more than 15 had some relevance to the technologies. The legislation was sorted by policy framework: climate and energy, waste and circular economy, products and labelling, environmental pollution, environmental risk, and environmental impact assessment.

Several policies in the climate and energy policy framework raise important issues with regard to CCU technologies.

The EU ETS has recently been revised so that CCU processes could potentially be exempt from surrendering EU allowances; however, the mechanisms for exemption need to be developed. As became apparent in stakeholder discussions, retention time is still a subject of debate and permanent storage offered by some CCU technologies is considered under the ETS as a possible criterion for exemptions. As this study has shown, retention time and permanent storage do not, on their own, offer any climate benefit from CCU but have implications with regard to how to attribute incentives under the ETS. What is needed is a full assessment of a CCU process' net CO_2 emissions in the production phase compared to the production of a fossil- or bio-based conventional process which it replaces. With regard to this approach we suggest that the new term of 'avoided emissions' introduced in Recital 14 of the revised ETS Directive could be defined using the comparative approach. However, the ETS framework is not currently capable of accounting for the potential climate benefits from CCU, due to the installation-based focus of the accounting and MRV processes, and for processes other than CCU mineralisation such as fuels where other and potentially more supportive incentive mechanisms exist which are less prone to regulatory loopholes, so the incentive should probably not be given under the ETS.

Renewable Energy Directive II has been revised, leading to CCU fuels being subject to being counted towards national renewable energy targets and supported by fuel-blending quotas if they are recognised as renewable. The methodology for determining whether a CCU fuel can be counted as renewable includes specific conditions following the principles that new and additional renewable energy is used or that energy from the national grid can be proven to be produced exclusively from renewable energy sources.

Other key issues could be identified in the waste and circular economy policy framework.

CCU can contribute to a circular economy and reduce the volume of virgin materials extracted by recycling carbon and carbon-based products. While this is beginning to be recognised in the EU circular economy framework, the Waste Framework Directive, which sets out the framework conditions for waste to be reused as input material for new products, is still the subject of different national interpretations due to the possible hazardous content of waste-based products (in particular incinerated waste) and leading to trade restrictions between Member States. This situation was noted in one case in particular, the production of aggregates from CCU mineralisation processes. Following the revision of the Waste Framework Directive in 2018, this issue may be addressed since the revised text empowers the European Commission to adopt EU-wide end-of-waste criteria following a consultation process.

Other less important issues could be identified in relation to some of the legislation.

The **development of options** (Task 2.2) was conducted in collaboration with stakeholders and led to the development of a set of four possible approaches containing specific options for addressing hurdles to the development of CCU technologies. At the same time the feasibility these of options was assessed.

Whereas, the main benefit of CCU technologies will be for the circular economy, the regulatory framework should acknowledge when there is contribution from CCU to EU climate objectives. A harmonised life-cycle assessment (LCA) is a first and indispensable step. The revised Renewables Directive is already giving the impetus for fuels. However, the EU needs to start rethinking the emissions monitoring framework for the period after 2030.

Under the EU ETS approach a future solution to the problem of carbon accounting under the ETS was proposed. Indeed, the ETS was shown to be unable to account for avoided GHG emissions in a CCU system where CO_2 is transferred outside the ETS, due to avoided emissions occurring outside the boundaries of single installations, and only when compared to a conventional production process. Consequently, the EU should consider other accounting systems, such as project-based accounting, which expand the boundaries of the accounting system. In the shorter term the EU can consider providing incentives to installations producing CCU products with potentially permanent storage of CO_2. This option makes possible the avoiding of internal carbon leakage, where CO_2 emissions reported as avoided under the ETS are in fact occurring outside of the ETS. The option of including CCU under the ETS must be considered in conjunction with other possible forms of incentives under other legislation in order to avoid double incentives and possible market distortions.

Other options can be introduced which do not involve altering the ETS. Under the products and labelling policy framework, a first option to implement blending quotas, as they exist for fuels, was explored, but for other products. This option could be effective; however, the conditions for its effectiveness must be further researched and defined. For instance, blending quotas should not be applied where EU products risk being in competition on international markets if similar market mechanisms do not exist in parts of the world which would be more competitive due to less regulation. Voluntary labelling of CCU products should be further explored in synergy with raising public awareness about what CCU is and its real advantages or disadvantages.

The waste and circular economy policy framework approach offers relevant options for incentivising CCU as a set of technologies for creating a more circular economy. Under the Waste Framework Directive harmonised end-of-waste criteria and by-product criteria would allow the categorising of waste as either new products or by-products, making possible a better acceptance of carbon-recycled products across the Common Market. The risk related to the possible presence of hazardous substances in reused materials should, however, still be mitigated by producers or it should be ensured that such do not cause harm by specifying safe uses of the product. Product safety is set out in product-specific legislation and standards which could be adjusted to recognise recycled products and their safety requirements for EU-wide application. Under the 'new approach' these requirements could be more flexibly introduced and accelerate take-up of CCU products in EU markets.

Under the Environmental pollution policy framework the IED is taken as a possible way to incentivise CCU processes which offer GHG and resource efficiency gains via the existing 'best available technique' and 'emerging technique' mechanisms. To recognise CCU processes as 'best available' or 'emerging' techniques thorough assessments would need to be conducted. For now, the requirements for being categorised as emerging techniques seem more within reach, due to the novelty of most CCU technologies and lack of information about their environmental impacts. This option should, however, not be seen as a priority, as it would be unlikely to lift significant or undue barriers to CCU deployment.

As a third approach we explored the potential for new policy specific to CCU. In this approach no new legislation was considered but a soft policy approach was proposed. The only option investigated was for the European Commission to collect knowledge about CCU and publish a communication setting out the EU's position regarding CCU and common definitions. Policy objectives could also be set out across sectors and policy areas. The work would gather stakeholders to agree on what the EU should aim for with regards to CCU deployment and help unify the discourse around this complex set of technologies.

The fourth and final approach considered not taking new policy decisions. In particular we discussed the option of not including CCU in the EU ETS in the near term. While there are good arguments for doing so, such as the lack of information about the GHG benefits of specific CCU technologies, the CJEU's preliminary ruling on the *Schaefer Kalk* case must be acknowledged and complied with. Furthermore, some form of recognition of CCU processes' potential GHG emission and resource efficiency benefits should be offered. Option 2 discussed not taking further policy steps except with regards to financing, where balanced financing across different types of CCU processes could allow for the development of resource-efficiency technologies in different sectors.

The **assessment of the options' impacts** (Task 2.3) was conducted on the basis of the findings of Task 1.3 and led to a set of recommendations for the EU to incentivise technologies while following the general principles and recommendations stated.

EU ETS options require a high degree of care in their design and implementation to avoid double counting and double incentivisation, thereby maintaining the environmental integrity of the system. Current options are targeted at different CCU product clusters, due to their specific environmental and economic characteristics (permanent storage for mineralisation products used in construction, re-emission of fuels in the transport sector leading to carbon leakage), which may lead to incentivisation of certain products over others or the use of these products in certain sectors. Project-based accounting of GHG emissions of CCU projects could lead to more industrial symbiosis projects.

Options under a piecemeal approach could lead to more market demand for CCU products; however, it is difficult to estimate their impact and the scale of this impact without further research. In theory, proper market incentives to environmentally beneficial CCU processes could lead to higher resource efficiency and reduced fossil fuel dependency by substituting recycled CO_2.

A CCU communication could contribute to clarifying the public discourse around CCU, with positive impacts in many areas and contributing to better policy and economic decision-making.

A lot has already been done for CCU under different legislation and for its financing. The last set of options considering a 'nothing-new policy' therefore may not be critically endangering the development of CCU; however, we recommend further developing the policy framework to continue to provide a framework for the proper deployment of CCU with due regard to the possible environmental impacts and to risks of undermining current policy objectives.

As final remarks, it is important to note that this study has been conducted on the basis of available knowledge and at a stage when the technologies are still in development. Close monitoring of their development and of the state of knowledge concerning their environmental benefits, and also how to measure these benefits, will be key for developing new policies on CCU. At present CCU technologies do not seem to offer important climate mitigation potential, and therefore should be considered against the higher potential that other policies and technologies can offer. CCU should, for instance, not replace efforts to introduce CCS.

Due to ongoing research on the topic of criteria for treating CCU under the ETS and attributing proper incentives to actors able to adequately demonstrate the climate benefits of their technologies, it is not recommended to take yet any measures for altering the functioning of the ETS in any significant way or in the short-term. Assessment of CCU technologies needs to be carried out for each project to account for the different process existing. It is likely that only once certain CCU processes will have been tried, established and shared can simpler approaches be taken, such as listing of most carbon-efficient CCU processes for less burdensome assessment and incentivisation mechanisms.

3.7 References for Task 2

Articles and publications

Bardow, A. and Green, D. (2018). Low-Carbon Process Industries Through Energy Efficiency and Carbon Dioxide Utilisation – A study in support of a DG Research & Innovation Projects for Policy (P4P) report. European Commission Directorate-General for Research and Innovation.

Bloomberg, 2018. Pollution Market Gets a Boost in EU With Move to Reduce Glut. Article 26 February 2018. https://www.bloomberg.com/news/articles/2018-02-26/pollution-market-gets-a-boost-in-eu-with-move-to-reduce-glut

Carbon Counts. (2014). Biomass and CCS – Guidance for accounting for negative emissions. IEAGHG. Retrieved from: https://ieaghg.org/docs/General_Docs/Reports/2014-05.pdf

Carbon Market Watch. (2014). Tackling 60% of the EU's climate problem – The legislative framework of the Effort Sharing Decision. Retrieved from: https://carbonmarketwatch.org/wp-content/uploads/2014/05/Report-Legislative-Framework-of-the-ESD-Carbon-Market-Watch_WEB.pdf

Christensen, A. and Petrenko, C. (2017). CO_2-Based Synthetic Fuel: Assessment of Potential European Capacity and Environmental Performance.

Ecofys and Carbon Counts. (2013). Implications of the Reuse of Captured CO_2 for European Climate Action Policies. By order of European Commission DG Climate Action.

European Commission. (n.d.). Use of international credits in EU ETS after 2020. Web. Retrieved from: https://ec.europa.eu/clima/policies/ets/credits_en

IEAGHG. (2018). Greenhouse Gas Emissions Accounting for Carbon Dioxide Capture and Utilisation (CCU) Technologies. 2018-TR01.

Mac Dowell, N., Fennel, P.S., Shah, N. and Maltland, G.C. (2017). The role of CO_2 capture and utilisation in mitigating climate change. Nature, April 2017, vol. 7, pp243-248.

Metz, Bert et. al. (2005). Intergovernmental Panel on Climate Change (IPCC) Special Report on Carbon dioxide capture and storage, UNEP, Cambridge University Press

Transport and Environment. (2017). Electrofuels – what role in EU transport decarbonisation?

Wilson et al. (2016). A Strategic European Research and Innovation Agenda for Smart CO_2 Transformation in Europe. SCOT Project.

Legal instruments and official documents

ARCO Chemie Nederland Ltd v. Minister van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer, Joined Cases C-418/97 and C-419/97 [2000] E.C.R. I-04475 para. 73

Commission Decision 2009/335/EC on the Technical guidelines for the establishment of the financial guarantee

Commission Decision 2009/337/EC on the Criteria for the classification of waste facilities in accordance with Annex III

Commission Decision 2009/358/EC on the Harmonisation, the regular transmission of the information and the questionnaire referred to in Articles 22(1) (a) and 18.

Commission Decision 2009/359/EC on the Definition of inert waste in implementation of Article 22 (1)(f)

Commission Decision 2009/360/EC completing the technical requirements for waste characterisation

Commission Directive 2014/80/EU of 20 June 2014 amending Annex II to Directive 2006/118/EC of the European Parliament and of the Council on the protection of groundwater against pollution and deterioration Text with EEA relevance

Commission proposal for a Regulation on the making available on the market of CE marked fertilising products and amending Regulations (EC) 1069/2009 and (EC) 1107/2009, COM(2016) 157 final, Brussels, 17 March 2016

Communication from the Commission promoting sustainable development in the EU non-energy extractive industry. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=legissum:l28113

Decision No 2009/607/EC Commission Decision of 9 July 2009 establishing the ecological criteria for the award of the Community eco-label to hard coverings (Notified under document C(2009) 5613) (Text with EEA relevance)

Decision 2014/391/EU: Commission Decision of 23 June 2014 establishing the ecological criteria for the award of the EU Ecolabel for bed mattresses (notified under document C(2014) 4083) Text with EEA relevance

Decision 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community’s greenhouse gas emission reduction commitments up to 2020

Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy

Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment

Directive 2004/35/CE of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage

Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration

Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the management of waste from extractive industries and amending Directive 2004/35/EC - Statement by the European Parliament, the Council and the Commission

Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy, amending and subsequently repealing Council Directives 82/176/EEC, 83/513/EEC, 84/156/EEC, 84/491/EEC, 86/280/EEC and amending Directive 2000/60/EC of the European Parliament and of the Council

Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance)

Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (Text with EEA relevance)

Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EE

Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) 1013/2006 (Text with EEA relevance)

Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control)

Directive 2011/92/EU of the European Parliament and of the Council of 13 December 2011 on the assessment of the effects of certain public and private projects on the environment Text with EEA relevance

Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC Text with EEA relevance

Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC (Text with EEA relevance)

Directive 2013/39/EU of the European Parliament and of the Council of 12 August 2013 amending Directives 2000/60/EC and 2008/105/EC as regards priority substances in the field of water policy Text with EEA relevance

Directive 2018/2001/EU of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance)

European Commission addresses barriers to innovation: the first Innovation Deal focuses on water reuse. Brussels, 7 April 2017. Retrieved from: http://ec.europa.eu/research/index.cfm?pg=newsalert&year=2017&na=na-070417

European Commission, A European Strategy for Plastics in a Circular Economy, COM(2018) 28 final, Brussels, 16 January 2018.

European Commission, Closing the loop – An EU action plan for the Circular Economy, COM(2015) 614 final, Brussels, 2 December 2015.

European Commission, Communication on the implementation of the circular economy package.

European Commission. (2018). Joint Declaration of Intent for the INNOVATION DEAL on 'From E-Mobility to recycling: the virtuous loop of the electric Vehicle'. Retrieved from: https://ec.europa.eu/research/innovation-deals/pdf/jdi_emobility_recycling_112017.pdf

European Parliament legislative resolution of 17 April 2018 on the proposal for a regulation of the European Parliament and of the Council on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry into the 2030 climate and energy framework and amending Regulation (EU) 525/2013 of the European Parliament and the Council on a mechanism for monitoring and reporting greenhouse gas emissions and other information relevant to climate change (COM(2016)0479 – C8-0330/2016 – 2016/0230(COD)) (Ordinary legislative procedure: first reading)

Judgment of the Court (First Chamber) of 19 January 2017 – Schaefer Kalk GmbH & Co. KG v. Bundesrepublik Deutschland - Request for a preliminary ruling from the Verwaltungsgericht Berlin. Case C-460/15. Retrieved from: http://curia.europa.eu/juris/liste.jsf?language=en&num=C-460/15#

Proposal for a Regulation of the European Parliament and of the Council on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 for a resilient

Energy Union and to meet commitments under the Paris Agreement and amending Regulation No 525/2013 of the European Parliament and the Council on a mechanism for monitoring and reporting greenhouse gas emissions and other information relevant to climate change, COM(2016)0482

Proposal for a Regulation of the European Parliament and of the Council on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry into the 2030 climate and energy framework and amending Regulation No 525/2013 of the European Parliament and the Council on a mechanism for monitoring and reporting greenhouse gas emissions and other information relevant to climate change, COM/2016/0479 final

Regulation (EC) 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and No 1999/45/EC, and amending Regulation (EC) 1907/2006 (Text with EEA relevance)

Regulation (EC) 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and No 1999/45/EC, and amending Regulation (EC) 1907/2006 (Text with EEA relevance)

Regulation (EC) 850/2004 of the European Parliament and of the Council of 29 April 2004 on persistent organic pollutants and amending Directive 79/117/EEC

Regulation (EC) 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) 793/93 and Commission Regulation (EC) 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, No 93/67/EEC, No 93/105/EC and No 2000/21/EC

Regulation (EC) 66/2010 of the European Parliament and of the Council of 25 November 2009 on the EU Ecolabel (Text with EEA relevance)

Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) 525/2013 and Decision 529/2013/EU (Text with EEA relevance)

Regulation (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (EU) 525/2013 (Text with EEA relevance)

Regulation (EU) 182/2011 of the European Parliament and of the Council of 16 February 2011 laying down the rules and general principles concerning mechanisms for control by Member States of the Commission’s exercise of implementing powers (OJ L 55, 28.2.2011, p. 13)

Regulation (EU) 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC

Regulation EC 166/2006 of the European Parliament and of the Council of 18 January 2006 concerning the establishment of a European Pollutant and Transfer Register and amending Council Directives 91/689/EEC and 96&61/EC

UNFCCC CDM. (2017). Cdm Methodology Booklet. Ninth edition. Retrieved from: https://cdm.unfccc.int/methodologies/documentation/meth_booklet.pdf

UNFCCC CDM. (n.d.). AM0027: Substitution of CO_2 from fossil or mineral origin by CO_2 from renewable sources in the production of inorganic compounds – Version 2.1. Retrieved from: https://cdm.unfccc.int/methodologies/DB/OE28MVRSBGJUV2CB9UB046N62HJ8CP

UNFCCC CDM. (n.d.). AM0063: Recovery of CO_2 from tail gas in industrial facilities to substitute the use of fossil fuels for production of CO_2 --- Version 1.2.0. Retrieved from: https://cdm.unfccc.int/methodologies/DB/NT2ICQVYYXJ1YGSOPV8FLULKNSN74C

<u>Websites</u>

EC Climate Action, Latest News 14 May 2018): https://ec.europa.eu/clima/news/regulation-land-use-land-use-change-and-forestry-2030-climate-and-energy-framework-adopted_en

EU Climate Action, 2030 climate & energy framework: https://ec.europa.eu/clima/policies/strategies/2030_en

EC Climate Action, Effort Sharing: Member States' Emission targets: https://ec.europa.eu/clima/policies/effort_en

European Council Press release 17 January 2018): http://www.consilium.europa.eu/en/press/press-releases/2018/01/17/effort-sharing-regulation/

European Council (23 and 24 October 2014) – Conclusions: http://data.consilium.europa.eu/doc/document/ST-169-2014-INIT/en/pdf

EC Climate Action, Effort Sharing 2021–2030: https://ec.europa.eu/clima/policies/effort/proposal_en

EC Climate Action, Land use and forestry regulation for 2021–2030): https://ec.europa.eu/clima/lulucf_en

EC Climate Action, Latest News 14 December 2017: https://ec.europa.eu/clima/news/commission-welcomes-agreement-key-legislation-tackle-climate-change_en

Innovate UK, 2 January 2014: https://www.gov.uk/government/case-studies/green-innovation-recycling-waste-into-building-blocks

EC DG Environment, Industrial Emissions Directive: http://ec.europa.eu/environment/industry/stationary/ied/legislation.htm

EC DG Environment, Ecolabel: http://ec.europa.eu/environment/ecolabel/

EC DG Environment, Product Groups and Criteria: http://ec.europa.eu/environment/ecolabel/products-groups-and-criteria.html

EC DG Environment, REFIT Evaluation of the SEA Directive: http://ec.europa.eu/environment/eia/sea-refit.htm

EC DG Environment, Introduction to the new EU Water Framework Directive: http://ec.europa.eu/environment/water/water-framework/info/intro_en.htm

EC DG Environment, Environmental Liability; http://ec.europa.eu/environment/legal/liability/index.htm

EC DG Environment, Major Accidents Hazards: http://ec.europa.eu/environment/seveso/

EC DG Environment, Sustainable Environment; http://ec.europa.eu/environment/eussd/escp_en.htm

EC DG Growth, Classification and Labelling (CLP/GHS): https://ec.europa.eu/growth/sectors/chemicals/classification-labelling_en

EC DG Growth, REACH: https://ec.europa.eu/growth/sectors/chemicals/reach_en

European Chemicals Agency, Registry of Intentions: https://echa.europa.eu/registry-of-intentions

European Chemicals Agency, Understanding CLP: https://echa.europa.eu/regulations/clp/understanding-clp:

EP Legislative Observatory, Procedure file 2016/0230(COD): http://www.europarl.europa.eu/oeil/popups/ficheprocedure.do?reference=2016/0230(COD)&l=en

Summary of stakeholder feedback to the Land Use, Land Use-Change and Forestry (LULUCF) proposal: https://ec.europa.eu/clima/sites/clima/files/docs/pages/summary_lulucf_stakeholder_feedback_final_en.pdf

UCL, Treating waste with carbon dioxide: http://www.ucl.ac.uk/impact/case-study-repository/treating-waste-with-carbon-dioxide

Appendices

4. Appendix Task 1

4.1 Technology Longlist

(See separate Excel file).

4.2 Technology Shortlist

(See separate Excel file).

4.3 Additions to Life Cycle Assessment

4.3.1 Introduction to the LCA

Establishing an industrial carbon cycle could lead to a lower input of primary fossil resources – in particular oil, coal or natural gas – for chemical production (Quadrelli et al. 2011; Peters et al. 2011). Currently, the chemical industry uses these fossil raw materials as sources of carbon and energy. The increasing availability of renewable energy, however, provides the option to separate carbon from energy sources. Carbon dioxide (CO_2) can be captured from flue gases or raw biogas, while renewable power can generate hydrogen (H_2) from water by electrolysis. These two inputs can then be combined to produce basic chemicals such as methane or methanol, which may be used for the production of polymers.

Following the utilisation phase of polymers, waste management can recover a part of the energy content and capture CO_2 from gases generated by incineration or biogas production. The use of CO_2 as raw material (in the following also called *alternative* routes) could thus complement the material recycling of carbon-rich materials such as waste plastics, and become part of an industrial carbon recycling which increasingly substitutes the linear flow of fossil carbon from the earth crust to the atmosphere.

Carbon capture and utilisation (*CCU*) is a growing field of research. It should be clearly distinguished from carbon capture and storage (CCS) where CO_2 is compressed and stored instead of producing chemicals (Bruhn et al. 2016).

An overview of CCU with possible routes for CO_2 utilisation and the policy context is given by Styring et al. (2011). Mikkelsen et al. (2010) give a chemical-based overview on transformation options of CO_2 to valuable products like methanol. Markewitz et al. (2012) provide a technical review of the status quo of CCU, including CO_2 and H_2 production and the synthesis of hydrocarbons.

Cuéllar-Franca and Azapagic (2015) present a summary of publications in the research area of CCU with a focus on the comparison of life-cycle environmental impacts. By considering sixteen studies on CCU, they identify post-combustion capture of CO_2 using monoethanolamine as one of the methods most applied for capturing CO_2. Only the study by Aresta and Galatola (1999) considers the production of CO_2-based chemicals via further reaction of captured CO_2 from post-combustion technologies and H_2. Their study conducts a life cycle assessment of CO_2-based dimethyl carbonate (DMC).

Trost et al. (2012) and Schaaf et al. (2014) consider CO_2-based methane production for energy storage of fluctuating renewable energies. Both of them analyze the quantitative potential of power-to-gas plants in Germany.

Besides methane, another focus of CO_2-based chemicals is on methanol. The potential use of methanol as fuel and feedstock was first described by Asinger (1986) who focused on the mobilization of coal. Olah et al. (2009) and Bertau et al. (2014) took up the idea of a "methanol economy", although with a focus on the practical use of hydrogen, which would allow becoming more independent of fossil fuels if hydrogen is produced with renewable energies.

Several studies consider options for the production of CO_2-based polymers. In this way, the catalytic copolymerization of epoxides with CO_2 for polyols and polycarbonates production is of special interest. For instance, Klaus et al. (2011) reviews several studies regarding reaction mechanism and research progress. Kember and Williams (2012) suggest to vary the reaction conditions. Bayer as chemical company toke up this idea for producing polyols from CO_2 and epoxides for polyurethanes (Langanke et al. 2014). Recently, Trott et al. (2016) summarize and review publications on ring-opening copolymerization of CO_2 and epoxides. Other CO_2-based polymers like methane and methanol derived ones are investigated rather rarely so far.

Life cycle assessments of CO_2-based basic chemicals, intermediates, and polymers were carried out in several studies. Von der Assen et al. (2013) provide a general insight in the methodology of environmental assessments in the field of CCU. Reiter and Lindorfer (2015) investigate the global warming impacts (GWI) of CO_2-based methane. Both of them conclude that the ecologic performance depends mainly on the scope, for instance, the electricity mix for electrolysis. Sternberg and Bardow (2015) focus on a life cycle assessment on GWI and fossil depletion of methane, synthesis gas, and methanol. They observe reductions of GWI for all CO_2-based chemicals. Schäffner et al. (2014) investigate different impacts like the GWI of fatty acid esters from CO_2. Von der Assen and Bardow (2014) analyze the GWI and other impacts of the production of CO_2-based polyols. A recent study from von der Assen et al. (2015) investigates the impacts of production and utilisation of polyoxymethylene units for polyurethane production. This study focuses on the GWI of the polymer. Cuéllar-Franca and Azapagic (2015) observe that the environmental assessment of their considered studies is mostly based on GWI of different products. Other common impact categories are acidification and eutrophication.

Recently published LCA studies on the production of CO_2-based chemicals like methane or methanol indicate that the GWI could be lowered compared to fossil-based production (von der Assen et al. 2013; Sternberg and Bardow 2015; Hoppe et al. 2016). The result, however, strongly depends on the energy source for electrolysis and the chosen CO_2 –input. Furthermore, the type of use (heat, electricity, chemical products) of the CO_2-based products influences their environmental performance.

So far, the following aspects have not yet been studied at all or at least not sufficiently:

Resource requirements: The material intensity of CCU needs to be investigated. As climate-friendly CCU requires renewable energies, the resource requirements for their infrastructure have to be considered. Resource policies in countries like Germany and Japan and in the EU demand higher resource efficiency (Bahn-Walkowiak and Steger 2015; EEA 2016). Their implementation requires a cross-scale application of material flow based indicators which have been adopted in statistical guidelines of European Commission (2001), Eurostat (2013), and OECD (2008), and become more and more established (Fischer-Kowalski et al. 2011; Schandl et al. 2016).

Process integration: Heat requirements for capturing CO_2 from different sources could be reduced by using waste heat from subsequent processes which might influence the environmental impacts of process chains (Zhang et al. 2015). As the thermal performance of processes for the production of base chemicals from CO_2 differ, varying options for process integration have to be considered.

The methanol-to-olefins (MTO) process chain: The MTO route is gaining increasing importance for the CO_2-based production of bulk chemicals (Olah et al. 2011) while its environmental performance is insufficiently considered so far. A detailed life cycle assessment of methane and methanol production as intermediate step for CO_2-based bulk chemicals is also required.

Our study intends to fill these research gaps and compares the CO_2-based and the conventional production methods of relevant chemicals. The third point leads to the question which chemicals could play an important role within a future CCU scheme and are relevant for our analysis.

We consider methane because it is a key platform chemical for methanol and CO_2-based polymers (Von der Assen et al. 2015). Methanol itself can be used for a large amount of CO_2-based final products, including polymers (Benvenuto 2014). Synthesis gas shall be considered as well because it is an intermediate for methanol production from methane (Benvenuto 2014).

We assess both PE and PP production as they are the most demanded polymers in Europe (PlasticsEurope et al. 2012). In contrast to those high volume polymers, polyoxymethylene (POM) is a specialty polymer. Its higher quality and price may make a market entry of CO_2-based POM more likely than for large volume low price polymers. POM is one of the few polymers whose carbon content could mostly be delivered from CO_2 without any fossil raw materials.

The goal of the study is to investigate key life-cycle performance indicators of selected CCU routes based on different sources of CO_2. Steinmann *et al.* (2016) found that the life-cycle-wide input of fossil energy, materials, land, and water ("resource footprints") together explains 84 % of the variance of all life cycle assessment (LCA) impact categories covered in a standard database such as ecoinvent. For our study we consider land and water less relevant and focus our analysis on a comparison of the *global warming impacts* (GWI) using the 100-year global warming potentials (GWP_{100}), the material input (*raw material input* (RMI) and the *total material requirement* (TMR)) of CO_2-based and conventional process chains.

4.3.2 LCA Methodology

General Approach

The process chains for the production of chemicals were analyzed by an attributional life cycle assessment. We used ecoinvent 3.1 as data basis in background processes (Weidema et al. 2013) and OpenLCA 1.4.1 as software for modelling and calculating. As a functional unit, we considered the production of 1 kg of methane, synthesis gas or methanol. Methane is considered to be delivered at 80 bar, taking into account the infeed into the public high-pressure gas grid. We used the methane content of CO_2-based and conventionally produced synthetic or natural gas, respectively, as comparable value, as we are only interested on chemical use of methane for synthesis gas and the regarded polymers. Further information on the calculation of the methane content and in consequence thereof the amount of natural gas needed for 1 kg of methane are provided in the Supplementary Material (section 1). For the polymers, 1 kg of POM, PE or PP is regarded as the functional unit.

The GWI is a measure for greenhouse gas (GHG) emissions. It is given in kg CO_2 equivalents (CO_2eq). Measuring the material use of chemical production, we calculated the input-oriented indicators RMI and TMR in kg. Both indicators are usually economy-wide indicators (European Commission 2001; OECD 2008; Eurostat 2013) but have also been developed for products and infrastructures. For instance, Wiesen et al. (2013) determined the TMR of wind power. The rationale of those mass flow based indicators has been described elsewhere (Bringezu et al. 2003). The idea behind both indicators is that they consider primary materials taken from nature. While RMI focusses on used materials only, the TMR is a measure for both used and "unused" primary materials (both purposefully moved). The former represents the product output of the primary sector (mining, agriculture etc.), the latter its input by technical means (total excavation, cuttings etc.). We are classifying material inputs in biotic and abiotic raw materials. Biotic raw materials are referring to plant biomass from cultivation and biomass from uncultivated areas. Abiotic raw materials comprise metals, industrial minerals, construction minerals and fossil fuels (Saurat and Ritthoff 2013). After developing and analyzing the process chains, we verify the results in a sensitivity analysis.

Process Chains

The process chains are classified according to the products methane, synthesis gas, methanol, POM, PE and PP. Five CO_2-sources (air, biogas, flue gases from cement, waste incineration and lignite-fired power plants) are considered for each product. We assume identical qualities of CO_2-based basic chemicals compared to the conventionally produced ones.

Technologies and data considered represent conditions in Western Europe. The potential CO_2-sources, which could be used in Germany and their specifications, are given in table 1. CO_2 from biogas and flue gases (cement production, lignite and waste incineration) are point sources with relatively high concentration of CO_2. Capturing CO_2 from air (also called *Direct Air Capture* (DAC)) has the advantage of being spatially independent but is challenged with a relatively low concentration of CO_2 in the air.

Amine scrubbing is used for CO_2 capture due to a high purity and amount of captured CO_2 (Markewitz et al 2012). CO_2 is absorbed by an amine-based substance (for example monoethanolamine (MEA)) and is thereby captured from flue gases. Heating then separates the solvent from CO_2 which evaporates and can be used for the following processes while the amine is regenerated. Cleaning of CO_2 after amine scrubbing is not necessary due to high purity of the gas. The need for electricity for CO_2-capturing is of minor importance (Markewitz et al 2012). Capturing CO_2 from air is considered as practiced by Climeworks company where a special kind of an amine-based compound is used (Gebald et al. 2012). The capture method is largely comparable to the described amine scrubbing, although the mentioned amine-based adsorbent might lead to slightly different capture characteristics.

The heat sources for CO_2-capture are given in Table 13 - Heat sources for CO2-capture.

Biogas and cement production itself are not affected by capturing CO_2, whereas a work loss in electricity production was assumed for lignite-fired power plants (additional energy from the lignite-fired power plant for CO_2-capture) and waste incineration plants (substituted by electricity from the grid). In contrast to biogas and cement plants, using heat to capture CO_2 is regarded as coupled to reduced power production in both plants. This is in line with other studies (Oyenekan and Rochelle 2006; Oyenekan and Rochelle 2007; Jassim and Rochelle 2006).

For methane production, heat for CO_2-capture from DAC, biogas and cement production is recovered directly from methanation which is a highly exothermic reaction. For methanol production, heat recovery is also assumed. However, as the reaction is less exothermic, only a small amount of heat can directly be used for CO_2-capture, and the main part is assumed to be delivered from external sources.

The production of synthesis gas and POM is based on methane. Polyolefins are produced on the basis of methanol. Methanol is assumed to be directly formed from H_2 and CO_2.

Table 13 - Heat sources for CO2-capture

CO_2-source	Methanation (also for synthesis gas & POM)	Methanol Synthesis (also for PE & PP)
Air	Heat recovery from methanation/natural gas burning	Heat recovery from methanol synthesis/natural gas burning
Biogas	Heat recovery from methanation	Heat recovery from methanol synthesis/natural gas burning
Cement plant	Heat recovery from methanation and kiln exhaust gases	Heat recovery from methanol synthesis and kiln exhaust gases/natural gas burning
Lignite-fired power plant	Work loss of lignite-fired power plant	Work loss of lignite-fired power plant
Waste incineration plant	Work loss of waste incineration plant	Work loss of waste incineration plant

The environmental impacts of incineration, biogas production, and cement production are not considered as uncaptured and unpurified CO_2 is classified as waste. This means that the economic value of CO_2 is around zero (it could also be negative with regard to CO_2 emission trade systems). The captured CO_2, however, is regarded as (valuable) raw material for the following chemical conversions (von der Assen et al. 2013). According to LCA conventions, a cut-off approach is followed. We account for the input of CO_2 into the system and its effect on GWI. The steps before capturing CO_2 (biogas production etc.) are not included. The life-cycle effects of the production of H_2 are considered to contain all upstream processes. In a cradle-to-gate analysis, the process chains begin with the raw material extraction and end with the provision of the final product. Further use and waste management of the chemicals are not accounted for. Transport processes are not considered.

H_2 is produced via electrolysis. The use of renewable energies for electrolysis is necessary if one does not want to accept higher GHG emissions by incinerating fossil fuels for energy production than GHG savings by using CO_2 (Ozbilen et al. 2013; Olah et al. 2009). We assume the supply of wind energy for electrolysis and the German electricity mix for all other processes. Wind power is a suitable energy source because it is the most important kind of all renewable energies in Germany (BMWi 2016). Due to the fact that surplus electricity has to be curtailed, wind power is mostly affected by curtailment (Bundesnetzagentur 2016). In addition, direct sourcing of wind power by CO2-processing plants may be possible through contracting or in case of close by location. We therefore focussed on wind power as an appropriate energy source for the electrolysis. The output of oxygen (O_2) from electrolysis is not further considered in our analysis.

Sabatier first described the production of methane from CO_2 and H_2 (also called methanation of CO_2) in 1902.

Methanation:

$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$ (ΔH_R^0= -253.2 kJ/mol) (3)

Although there are different options for the production of synthesis gas, we consider SMR for the production of CO_2-based synthesis gas (equation 2). Other processes for synthesis gas production like dry reforming or reverse water gas shift reaction limit the number of suitable industrial processes due to their stoichiometry (Schwab et al. 2015). Furthermore, SMR is state of the art (Moseley and Garche 2014; Schwab et al. 2015). As the same process is used for the production of conventional synthesis gas, synthesis gas from CCU and from natural gas are comparable.

Steam methane reforming (SMR):

$CH_4 + H_2O \rightarrow CO + 3\ H_2$ (ΔH_R^0= +206.4 kJ/mol) (4)

CO_2 and H_2 are also the sole inputs in the CO_2-based methanol production (equation 3). Compared to methane, however, a smaller stoichiometric amount of CO_2 and H_2 is needed for the production of 1 kg of methanol.

CO_2-based methanol synthesis:

$CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$ (ΔH_R^0= -49.2 kJ/mol) (5)

The production of CO_2-based and conventionally produced basic chemicals are visualized in section 2-5 of the Supplementary Material.

We consider conventional methane as a component of natural gas. The production of natural gas includes all upstream processes such as resource extraction, purification, and transport in pipelines to and within Germany. The German market for natural gas in 2014 serves as a reference for the origin of natural gas (bafa 2015).

Carbon monoxide (CO) and hydrogen as components in conventional synthesis gas (molar ratio of $CO:H_2$ = 1:3) are produced via SMR from methane from natural gas and water.

Methanol from natural gas is produced via SMR from synthesis gas. The production of methanol from SMR-based synthesis gas is assumed to take place in Germany.

Conventional methanol synthesis:

$CO + 2\ H_2 \rightarrow CH_3OH$ (ΔH_R^0= -90.4 kJ/mol) (6)

The differences of CO_2-based and conventionally produced POM are premised on different reactants (we considered CO_2-based methane and methane from natural gas as reactants for the required methanol production according to PlasticsEurope (2011)). The other reaction pathways (polymerization and so on) are identical and therefore not differentiated.

We consider two types of POM: POM-h (homopolymer) and POM-c (co-polymer). In both cases, formaldehyde is produced via partial oxidation of methanol (equation 5). POM-h is produced by polymerization of formaldehyde (equation 6). The production of POM-c is slightly different. A various number of co-monomers can be used to produce a copolymer. The data we used reflect a mix of both reaction types of POM (PlasticsEurope 2011)

Partial oxidation:

$CH_3OH + ½ O_2 \rightarrow CH_2O + H_2O$ (ΔH_R^0= -157 kJ/mol) (7)

Polymerization:

$n * CH_2O \rightarrow -(CH_2O)-_n$ (8)

The amount of carbon in POM mostly (>99.5 %) originates from CO_2. The low input of 0.35 kg methane per kg POM results stoichiometrically from other non-carbon inputs, especially water and oxygen. Water is used as a co-reactant in steam reforming (equation 2) for the production of synthesis gas which is used for methanol synthesis. Oxygen is the co-reactant in partial oxidation of methanol (equation 5) for formaldehyde production.

While ethylene and propylene (called olefins) are produced from CO_2-based methanol via MTO-process (see equation (7) for ethylene (C_2H_4) production as an example), dimethyl ether serves as an intermediate. Polymerization of both olefins is the final production step to PE and PP.

MTO-process (ethylene prod.):

$2\ CH_3OH \rightarrow \boldsymbol{CH_3OCH_3} + H_2O; \quad \boldsymbol{CH_3OCH_3} \rightarrow C_2H_4 + H_2O$ (9)

Crude oil is the basis for the production of conventional polyolefins. It is cracked and processed into ethylene, propylene, and other components. The polymerization step of ethylene and propylene to PE and PP is considered to be equal for conventional and CO_2-based polyolefins.

Spatial classification of processes and consideration of transport impacts

The base scenarios neglect all transport processes of CO_2 and H2. It is assumed that the exploitation of the main raw materials and the conversion to basic chemicals and polymers occurs at the same place. To further quantify and evaluate the impacts of possible transports, relevant spatial scenarios are designed. In all cases, it is assumed that the electrolysis takes place in northern Germany. For an intended use of CO_2-based methane or methanol in close proximity of 50 km (regional scenario) or in southern Germany with an assumed distance of 500 km (long-distance scenario) two options are available represented in the following graphic. The first option (a) contains the transport of H2 in the natural gas pipeline. It is assumed, that at the target location the H2 can be extracted from the pipeline or that a hydrogen pipeline will be set up (Robinius, 2016). Furthermore, a CO_2 source has to be available at the target location. The second option (b) arises from the transport of the CO_2 based products. The production of CO_2 and H_2 as well as the synthesis of methane and methanol therefore happen at the same place. Methane will be transported in the pipeline and methanol by truck. In the scenarios, biogas is considered as CO_2-source.

For the electrolysis, a pressure of 50 bar is assumed (Hotellier 2014), the methanation takes place with 8 bar pressure. A first differentiation takes at the feed. In the regional scenario H_2 or CO_2-based methane is fed in the low-pressure grid (1 bar) without additional compression and transported over a distance of 50 km. The plant operators favour the injection in the low-pressure grid, because an additional compression is not necessary and therefore they have reduced costs (Burghart 2014). In the long-distance scenario H_2 or CO_2-based methane are compressed and fed in the high pressure grid at 80 bar. The assumed transport distance is 500 km. The transport of liquid methanol in trucks takes place without further compression.

Energy supply scenarios

The energy supply for the electrolysis is based on two options. On the one hand, the direct use of wind power or power from photovoltaic systems, close to renewable energies, is possible. On the other hand, the production systems can be connected to the public grid to use the power at a high network capacity utilisation and thereby balance the load curve. Both options reflect a discontinuous procedure of the electrolysis and are closer looked at in the following energy-scenarios.

Energy supply from wind power

Wind power is recognized as a central pillar of the energy transition [Nitsch et al., 2012], which makes a separate analysis of this energy source unreliable. If only power from nearby wind power stations were used for the hydrogen production by electrolysis, the use of power from the public grid would be redundant. With the background of a maximum utilisation rate of renewable energies this scenario would correspond to the ideal case. The exclusive usage of power from wind has already been examined in various research projects. The examination of Pereira & Coelho [2013] refers to an improved environmental balance. Menanteau et al. [2011] note that a hydrogen production exclusively based on wind power is connected to higher costs. Significant examples for the production of CO_2-based methane from wind power are the energy supply of the hydrogen competence centre H2Herten [Klug, 2010] as well as the demonstration project RH2 – WKA [Wind-projekt, 2012]. In both examples hydrogen functions as energy storage to store fluctuating wind energy. At the hydrogen competence centre H2Herten one wind power station is connected to the research centre, to a battery system for short-term storage of electric power and to an electrolyser. If the production exceeds the demand of the research centre, electric power will be stored temporarily in the battery. As soon as the capacity of the battery module is exhausted, hydrogen is produced via electrolysis, which will later be converted to electric power, so that long lasting lacks of wind will not be a problem. The concept of the demonstration project RH2 – WKA is similar. The power of multiple wind power stations is directly fed-in the public grid. In the case of a low intake capacity of the grid (for example through a low demand), the electrolyser produces hydrogen, which will later be converted (demand-based) to power and heat in a combined heat and power plant. The basis-scenarios assume that wind power is exclusively considered for the electrolysis to produce hydrogen. The German electricity mix from the public grid is responsible for the energetic input of all other processes.

Energy supply at high grid workload

The location of an electrolyser underlies geographical constraint, if the power supply shall be mainly through renewable energies. From a site-specific view especially northern Germany can be considered because of its high amount of wind power [Breuer et al., 2012]. The planned expansion of very-high-voltage lines from northern- to southern Germany is stated in the "Netzentwicklungsplan Strom" (power network development plan) of the Federal Network Agency [50Hertz Transmission GmbH et al., 2016]. Compared to the construction of power stores, the preferred expansion of the electricity grid is economically reasonable, because through a highly effective power grid and less network bottlenecks, the demand of storages in northern Germany will decrease [Graf et al., 2014]. Nevertheless, no decisive impulse emerges for potential power-to-gas locations in middle and southern Germany [Breuer et al., 2012; Jentsch et al., 2014]. That way even an optimised grid expansion will result in an excess supply of power mainly in northern Lower Saxony and Schleswig-Holstein in the year 2050 [Jentsch et al., 2014; Jentsch & Trost, 2014; Jentsch, 2015]. The excess supply of power in southern Germany, especially in Bavaria, will turn out lower [Jentsch & Trost, 2014; Jentsch, 2015].

Essential for the use of grid power in times of an excess supply is the storage of renewable energies: If caused by the weather an excessive amount of renewable energy is fed in the public grid, an excess supply will occur (negative residual load) and the spot price for electricity will decrease. In practice this is pushed through the priority feed-in of renewably generated electricity (§11 Abs. 1 EEG) and low marginal costs of renewable energies (especially wind power and photovoltaic). To stabilise the frequency of 50 Hz in the power grid, this energy supply (feeding volume) has to be reduced through a down-regulation of electric power plants. Alternatively, the surplus could be used through a rise in demand. The reduced power injection from renewable energies is caused by the network operators and labelled as feed-in management. The legal basis for the down-regulation of renewable electric power plants is formalized in § 14 Paragraph. 1 EEG (renewable energies law). The EEG feed-in management can also happen according to § 13 Energiewirtschaftsgesetz (EnWG) if an endangerment of the grid security and reliability is given.

Carbon capture and utilisation of CO_2 is an opportunity to minimize the loss of electricity production (surplus power; the amount of energy that could have been produced, if the windmill would not have been shut down) and to cover the electricity demand of the energy intensive electrolysis. In the case of a later electricity demand, the synthesized chemicals can be transferred to electrical energy or be used as raw materials. The CO_2 recycling would undertake a storage function and thereby take care for a balanced residual load in the power grid. So far only individual power storages (pumped-storage power plants) stabilise the grid frequency. The growing use of power storages only makes sense at high load fluctuations. Those are usually caused by renewable energies. Adamek et al. [2012] and Breuer et al. [2012] declare 40-60% as a reasonable quantity of renewable energies in the electricity mix. If the share is under this percentage, the load fluctuations will be balanced through conventional power plants. Furthermore, the is a risk, that the power storage is only used to an insufficient degree and therefore cannot be used economically. Only if higher percentages of renewable energies in the power grid are achieved, chemical power storages like hydrogen or CO_2-based methane play an important role at the German energy supply.

Measured based on the fed energy, the share of renewable energies was at 31.6 % in 2015 [BMWi, 2016]. The relative amount of wind power was in the same year 11.9 % [BMWi, 2016]. According to the energy concept of the German government from 2010, the share of renewable energies should be at 35 % in 2020, at 50 % in 2030 and at 80 % in 2050 [Bundesregierung, 2010]. Electricity from renewable energies can be traded to the grid operator for a fixed tariff (§ 19 Paragraph. 1 Nr. 2 EEG). To prevent an abuse due to the monopoly position of the network operators, they are legally bound through the "Erneuerbare-Energien-Verordnung (EEV)" (renewable energies regulation). Another opportunity is the direct commercialization through the electricity exchange EPEXSot (spot market) in Paris (§ 19 Paragraph. 1 No. 1 EEG or § 20 EEG or other direct trading § 21a EEG).

The direct marketing takes place through the plant operator and is usually obligatory according to § 21 Paragraph. 1 No. 1 EEG, if the plant performance exceeds 100 kWp. This performance-related limitation and the prospect of a higher return lead to a growing importance of direct marketing [BDEW, 2015; Schrader et al., 2015]. The purchase of electricity at the spot market takes place hourly the day before (Day-Ahead-Market) or at intervals of 15 minutes the same day no later than 30 minutes prior to the delivery time (intra-day trading). In the case that plants for CO_2 capture and utilisation (C-Rec-plants) are operated in times with negative residual load, plant operators can directly take part at the electricity trade of the EPEX spot market and buy the needed amount of electricity block by block. The consideration to purchase electricity in times with a high grid utilisation requires an analysis of the day-ahead market.

4.3.3 Data Basis for the LCA

The table in the Supplementary Material (section 6) provides a comprehensive overview of the life cycle inventory data. Key assumptions and data are explained here. 0.25 kWh electricity and 1.75 kWh heat are required if 1 kg CO_2 is captured from air (Wurzbacher 2014). These are technical data of a capture plant from Climeworks. We assumed biogas with a CO_2 content of 49 %. In this case, capturing CO_2 requires 0.11 kWh electricity and 0.67 kWh heat per kg CO_2 (MT-Biomethan GmbH 2012). Heat recovery from exhaust kiln gases for CO_2-capture in cement plants (0.34 kWh/kg CO_2) was calculated based on data from Engin and Ari (2005). Regardless of heat recovery, 0.02 kWh electricity and 1.20 kWh heat are required for capturing 1 kg CO_2 from a cement plant (Element Energy Ltd. et al. 2014). The calculation of the energy requirement for waste incineration is equal to the requirement in a lignite-fired power plant (efficiency loss of 6.5 %). We assumed electricity from the grid as a substitute for less exported energy for the waste incineration plant and higher lignite use for the lignite-fired power plant. The reason for this assumption is the availability of the feed: using electricity from a waste incineration plant can hardly be compensated by incinerating more waste. While the purpose of the waste incinerator is to convert the available waste to energy, the purpose of a lignite-fired power plant is to generate electricity (and heat). A growing internal energy demand would be compensated by incinerating a higher amount of lignite in the first place. Therefore, we considered a work loss of 0.24 kWh/kg CO_2 for the waste incineration plant and of 0.164 kWh/kg CO_2 for the lignite-fired power plant (Rochelle et al. 2011). This is in line with Moser (2015) who refers to an existing lignite-fired power plant in Niederaußem, Germany. Values for the work loss in lignite-fired power plants found in the literature are slightly higher. For instance, Zhang et al. (2015) calculate 0.23 kWh work loss/kg CO_2. Vasudevan et al. (2016) assume 0.22 kWh work loss/kg CO_2. Slightly different capture plants and processes may explain the difference.

As inputs for water electrolysis, we consider a wind power input of 54.73 kWh/kg H_2 and an ultrapure water requirement of 8.92 kg H_2O/kg H_2 (BTS et al. 2014 and Hotellier 2014). Oxygen as a by-product from electrolysis was not considered for further use.

The production of methane was calculated with information from the simulation of Müller et al. (2011). We assumed an electrical power input of 0.33 kWh/kg methane, a carbon dioxide requirement of 2.75 kg CO_2/kg methane and a hydrogen input of 0.52 kg H_2/kg methane. Due to negative reaction enthalpy of methanation, we considered a heat recovery of 1.02 kWh/kg CO_2 for CO_2-capture. The methane concentration in the CO_2-based product is 97.5 % (Müller et al 2011). In natural gas, it is around 90.4 % (DVGW 2011; bafa 2015; WEG 2015).

The methanation of equation 1 is the first step of synthesis gas production. The second step (SMR) is equal for both conventional and CO_2-based methane. We adopted data from BTS et al. (2014) and assumed an input of 0.71 kWh electricity/kg synthesis gas, 1.96 kWh heat from natural gas/kg synthesis gas, 0.53 kg ultrapure water/kg synthesis gas, and 0.47 kg natural gas/kg synthesis gas.

We took data for methanol production from the simulation by Rihko-Struckmann et al. (2010) and considered a material input of 1.37 kg CO_2/kg methanol, 0.19 kg H_2/kg methanol and a power input of 1.27 kWh electrical energy/kg methanol. The output of heat due to the exothermic reaction is relatively low (0.10 kWh/kg methanol).

Data for POM production were mostly adopted from PlasticsEurope (2011). For instance, we used these data directly for the calculation of conventional POM production from natural gas. CO_2-based POM was calculated by exchanging methane from natural gas into the equivalent amount of CO_2-based methane (0.35 kg methane/kg POM). The used process in the LCA model is a black-box model.

Data for the production of polyolefins were taken from different sources. We used data from ecoinvent 3.1 for the production of conventional high-density polyethylene (PE-HD) and polypropylene granulate from crude oil. For the MTO-process (production of olefins from methanol), data from Xiang et al. (2014) were considered for both ethylene and propylene. We calculated an input of 2.57 kg methanol, 0.46 kWh electrical energy, and 1.55 kWh steam per kg olefin. The polymerization as the last step of polyolefin production was calculated with data from Keim (2006). We considered the "Ziegler-process" for the production of high-density polyethylene (PE-HD). Regarding this process, we assumed an input of 1.015 kg ethylene, 0.015 kg butene, 0.45 kWh electricity, 0.4 kg steam and 0.17 m³ cooling water under normal conditions per kg PE. Assuming a turnover of about 98 % propylene for 1 kg of PP in the gas-phase polypropylene process, we considered a propylene requirement of 1.02 kg, an electricity input of 0.33 kWh, a steam input of 0.2 kg and an input of cooling water of 0.085 m³ under normal conditions per kg PP (Keim 2006).

Data for the energy infrastructure (pipelines, cables, power and heat generation etc.) are included in all ecoinvent processes as described above. We do not consider the construction of the methane, methanol, steam methane reforming, and polyolefin production plant of the CO_2-based process chains due to lack of data and assume negligible impacts. This is in line with other LCA studies on CCU (for example Collet et al. 2016 or Reiter and Lindorfer 2015).

Table 14: Average composition of the GER grid mix [%] and share with a sport price below 3 ct/kWh. Data for 2012 (Hoppe 2018)

Energy source	Share with spot prices < 3 ct/kWh)	Average total share
Lignite	29.35	29.76
Hard coal	5.74	13.73
Gas	2.76	3.54
Nuclear	21.44	20.45
Running water	4.40	3.82
Oil	0.33	0.49
Pumped storage	0.53	1.02
Photovoltaics	5.25	5.23
Wind offshore	0.26	0.15
Wind onshore	17.65	10.62
Biogas	9.84	5.64

4.3.4 Global warming reduction potentials for the European Union

<u>Calculation principle & data basis</u>

The calculations have been carried out for methane, methanol, polyethylene, polypropylene, polyoxymethylene, polyurethane and synthetic diesel. Scenarios are based on the CO_2 source with the highest and the lowest global warming impacts. Second lowest impacts were chosen where lowest impact route led to an overall GWI increase. Synthetic fuels was calculated using DAC with or without heat utilisation.

EU-Demand is based on the current production and import volume of the respective substance in the European Union.

Required electrical energy is based on electricity used to run the process. Electricity that is used to produce process equipment for example is not included. Data can be found in the LCA-Inventory.

Remarks give information on specific assumptions required.

Share of EU GWP based on an annual EU GWI of 4.4 Gt CO_2eq in 2015 (Eurostat 2018)

Share of renewable electricity based on EU renewable electricity production of 1258 TWh/a in 2020 (34,5% of 3645 TWh total electricity production) as assumed in the "Current Policies Incentive" Scenario of the "Energy Roadmap 2050" (European Union 2011). Results are listed in the following tables:

Methane:

Table 15 - GWI reduction potential and electricity demand for Methane

Methane							
	Substitution-Scenario	Share of EU Production & Imports	Methane [Mt/a]	GWI Reduction [Mt/a]	Required electrical energy for production [TWh]	Share of EU GWI	Share of EU ren electricity production
Substitution of Methane based on cement plant capturing reduction (highest GWI reduction)	Domestic EU production	23,80%	87,5	219,5	2.519,9	4,99%	200,31%
	Half EU demand	50,00%	183,8	461,2	5.293,8	10,48 %	420,81%
	Imports to EU	76,20%	280,0	702,9	8.067,8	15,97 %	641,32%
	Full EU demand	100,00%	367,5	922,4	10.587,7	20,96 %	841,63%

	Substitution-Scenario	Share of EU Production & Imports	Methane [Mt/a]	GWI Reduction [Mt/a]	Required electrical energy for production [TWh]	Share of EU GWI	Share of EU ren electricity production
Substitution of Methane based on DAC reduction (Lowest GWI reduction)	Domestic EU production	23,80%	87,5	138,2	2.540,0	3,14%	201,91%
	Half EU demand	50,00%	183,8	290,3	5.336,1	6,60%	424,17%
	Imports to EU	76,20%	280,0	442,5	8.132,2	10,06 %	646,44%
	Full EU demand	100,00%	367,5	580,7	10.672,2	13,20 %	848,35%

Methanol:

Table 16 - GWI reduction potential and electricity demand for Methanol

Methanol							
Substitution of Methanol based on cement plant capturing reduction (highest GWI reduction)	Substitution-Scenario	Share of EU Production & Imports	Methanol [Mt/a]	GWI Reduction [Mt/a]	Required electrical energy for production [TWh]	Share of EU GWI	Share of EU ren electricity production
	Domestic EU production	15,00%	1,2	1,1	14,3	0,03 %	1,14%
	Half EU demand	50,00%	4,0	3,8	47,6	0,09 %	3,79%
	Imports to EU	85,00%	6,8	6,4	81,0	0,15 %	6,44%
	Full EU demand	100,00%	8,0	7,6	95,3	0,17 %	7,57%
Substitution of Methanol based on DAC reduction (Lowest GWI reduction)	Substitution-Scenario	Share of EU Production & Imports	Methanol [Mt/a]	GWI Reduction [Mt/a]	Required electrical energy for production [TWh]	Share of EU GWI	Share of EU ren electricity production
	Domestic EU production	15,00%	1,2	0,4	14,3	0,01 %	1,14%
	Half EU demand	50,00%	4,0	1,5	47,7	0,03 %	3,79%
	Imports to EU	85,00%	6,8	2,5	81,1	0,06 %	6,45%
	Full EU demand	100,00%	8,0	2,9	95,4	0,07 %	7,58%

Polyethylene:

Table 17 - GWI reduction potential and electricity demand for PE

Polyethylene (PE)							
Substitution of Polyethylene based on WIPP capturing reduction (highest GWI reduction)	Substitution -Scenario	Share of EU Production & Imports	PE [Mt/a]	GWI Reduction [Mt/a]	Required electrical energy for production [TWh]	Share of EU GWI	Share of EU ren electricity production
	Domestic EU production	70,25%	2,0	1,9	59,5	0,04%	4,73%
	Half EU demand	50,00%	1,4	1,4	42,4	0,03%	3,37%
	Imports to EU	29,75%	0,9	0,8	25,2	0,02%	2,00%
	Full EU demand	100,00%	2,9	2,8	84,7	0,06%	6,73%
Substitution of Polyethylene based on biogas reduction (Lowest GWI reduction, DAC with GWI increase)	Substitution -Scenario	Share of EU Production & Imports	PE [Mt/a]	GWI Reduction [Mt/a]	Required electrical energy for production [TWh]	Share of EU GWI	Share of EU ren electricity production
	Domestic EU production	70,25%	0,3	0,2	8,8	0,01%	0,70%
	Half EU demand	50,00%	0,4	0,3	12,5	0,01%	1,00%
	Imports to EU	29,75%	0,9	0,6	25,1	0,01%	1,99%
	Full EU demand	100,00%	2,9	2,2	84,3	0,05%	6,70%

Polypropylene:

Table 18 - GWI reduction potential and electricity demand for PP

Polypropylene (PP)							
Substitution of Polyethylene based on WIPP capturing reduction (highest GWI reduction)	Substitution-Scenario	Share of EU Production & Imports	PP [Mt/a]	GWI Reduction [Mt/a]	Required electrical energy for production [TWh]	Share of EU GWI	Share of EU ren electricity production
	Domestic EU production	91,74%	10,3	12,3	304,4	0,28%	24,20%
	Half EU demand	50,00%	5,6	6,7	165,9	0,15%	13,19%
	Imports to EU	8,26%	0,9	1,1	27,4	0,03%	2,18%
	Full EU demand	100,00%	11,3	13,4	331,9	0,31%	26,38%
Substitution of Polyethylene based on biogas reduction (Lowest GWI reduction, DAC with GWI increase)	Substitution-Scenario	Share of EU Production & Imports	PP [Mt/a]	GWI Reduction [Mt/a]	Required electrical energy for production [TWh]	Share of EU GWI	Share of EU ren electricity production
	Domestic EU production	91,74%	0,4	0,4	12,5	0,01%	1,00%
	Half EU demand	50,00%	0,5	0,5	13,6	0,01%	1,09%
	Imports to EU	8,26%	0,9	0,9	27,3	0,02%	2,17%
	Full EU demand	100,00%	11,3	10,9	330,5	0,25%	26,27%

Polyoxymethylene:

Table 19 - GWI reduction potential and electricity demand for POM

Polyoxymethylene							
Substitution of POM based oncement plant capturing reduction (highest GWI reduction); 4)	Substitution-Scenario	Share of EU Production & Imports	POM [Mt/a]	GWI Reduction [Mt/a]	Required electrical energy for production [TWh]	Share of EU GWI	Share of EU ren electricity production
	25% EU	25,00%	0,1	0,0	NA	0,001 %	NA
	50% EU	50,00%	0,1	0,1	NA	0,002 %	NA
	75% EU	75,00%	0,2	0,1	NA	0,003 %	NA
	100% EU	100,00 %	0,2	0,2	NA	0,004 %	NA
Substitution of POM based on DAC reduction (Lowest GWI reduction, DAC with GWI increase); 4)	Substitution-Scenario	Share of EU Production & Imports	POM [Mt/a]	GWI Reduction [Mt/a]	Required electrical energy for production [TWh]	Share of EU GWI	Share of EU ren electricity production
	25% EU	25,00%	0,0	0,0	NA	0,000 %	NA
	50% EU	50,00%	0,1	0,0	NA	0,001 %	NA
	75% EU	75,00%	0,2	0,1	NA	0,002 %	NA
	100% EU	100,00 %	0,2	0,1	NA	0,003 %	NA

Polyurethanes:

Table 20 - GWI reduction potential for PU (from polyethercarbonate polyols)

Polyurethanes							
Substitution of PU based on 30 wt% incorporation of CO2 (highest GWI reduction) 5)	Substitution-Scenario	Share of EU Production & Imports	PU [Mt/a]	GWI Reduction [Mt/y]	Required electrical energy for production [TWh]	Share of EU GWI	Share of EU ren electricity production
	25% EU	25,00%	0,8	2,5	NA	0,06%	NA
	50% EU	50,00%	1,6	4,9	NA	0,11%	NA
	75% EU	75,00%	2,5	7,4	NA	0,17%	NA
	100% EU	100,00%	3,3	9,8	NA	0,22%	NA
Substitution of PU based on 10 wt% incorporation of CO2 (lowest GWI reduction) 5)	Substitution-Scenario	Share of EU Production & Imports	PU [Mt/a]	GWI Reduction [Mt/y]	Required electrical energy for production [TWh]	Share of EU GWI	Share of EU ren electricity production
	25% EU	25,00%	0,3	0,4	NA	0,01%	NA
	50% EU	50,00%	1,2	1,6	NA	0,04%	NA
	75% EU	75,00%	2,5	3,1	NA	0,07%	NA
	100% EU	100,00%	3,3	4,2	NA	0,09%	NA

Synthetic diesel:

Table 21 - GWI reduction potential and electricity demand for synthetic diesel

Synthetic diesel							
Substitution of diesel based on DAC with waste heat utilisation & GE Windpower (high, comparable GWI reduction); 1), 2)	Substitution -Scenario	Share of EU Production & Imports	Syn Fuels [Mt/a]	GWI Reduction [Mt/a]	Required electrical energy for production [TWh]	Share of EU GWI	Share of EU ren electricity production
	25% EU	25,00%	41,8	131,7	828,4	2,99%	65,85%
	50% EU	50,00%	83,6	263,3	1.656,8	5,98%	131,70%
	75% EU	75,00%	125,4	395,0	2.485,2	8,98%	197,55%
	100% EU	100,00%	167,2	526,6	3.313,6	11,97 %	263,40%
Substitution of diesel based on DAC with natural gas heat utilisation & GE windpower (low, comparable GWI reduction); 1), 3)	Substitution -Scenario	Share of EU Production & Imports	Syn Fuels [Mt/a]	GWI Reduction [Mt/a]	Required electrical energy for production [TWh]	Share of EU GWI	Share of EU ren electricity production
	25% EU	25,00%	15,7	31,7	310,6	0,72%	24,69%
	50% EU	50,00%	62,7	34,5	1.242,6	0,78%	98,78%
	75% EU	75,00%	125,4	69,0	2.485,2	1,57%	197,55%
	100% EU	100,00%	167,2	92,0	3.313,6	2,09%	263,40%

Remarks & Assumtions for the GWI calculation:
1) conversion factor 45 Mj/kg based on https://www.engineeringtoolbox.com/fossil-fuels-energy-content-d_1298.html

2) GWI Reduction from Universität Stuttgart (2015) assumed to be3,01, Electricity demand of 1.59 MJ/MJ Fuel

3) GWI Reduction from Universität Stuttgart (2015) assumed to be 1,49, Electricity demand of 1.59 MJ/MJ Fuel

4) POM results have been calculated with blackboxmodel from plastics Europe (2011). No split electricity demand available to calculate renewable electricity demand

5) Polyol demand has been calculated based on the production and imports volume for polyurethane (PU). We assume that the polyol is responsible for the main share of the polyurethane weight. The composition for the final Covestro PU is not known. We assume that GWI reduction for Polyols is representative for the complete PU production. **This assumption is very speculative** as the isocyanate share in the polyurethane cannot be substituted from the evaluated process. We used the GWI reduction indicated in Von Der Assen and Bardow (2014) including GWI benefit for the production of energy.

4.3.5 Supporting Information on the LCA

This supporting information provides information on methane as component of natural gas (section 1), the figures of the considered process chains (section 2-5), a life cycle inventory table (section 6), calculation tables for the GWI reduction achievable if CCU processes would be used within the EU (section 7) and changes of base metal process data due to inconsistencies in the ecoinvent database (section 8). We visualized in section 2-5 both the CO_2-based and the conventional process chains which are the basis for the life cycle assessment. Due to the comprehensive processes, we focused on the most important steps and the material exchange with the environment. The system boundary identifies the relevant processes for the life cycle assessment.

Section 1: Calculation of the methane content in natural gas

With regard to bafa (2015) and WEG (2015), we assume the following composition of natural gas (values correspond to the German imports in 2014; "other countries" with smaller amounts were neglected):

-Russia: 36.5 %

-Norway: 31.4 %

-The Netherlands: 22.7 %

-Germany: 9.4 %

The methane contents refer to DVGW (2011):

-Natural gas from Russia: 96.96 %

-Natural gas from Norway: 88.71 %

-Natural gas from The Netherlands: 83.64 %

-Natural gas from Germany: 86.46 %

By multiplying each methane content with the amount of natural gas, we calculate an overall methane content of 90.36 %:

36.5 % * 0.9696 + 31.5 % * 0.8871 + 22.7 % * 0.8364 + 9.4 % * 0.8646 = 90.36 %.

The assumed methane content of natural gas in Germany is around 90.36 %. Calculating the amount of natural gas, we multiplied the wanted amount of methane by 1.11 (100 %/90.36 % = 1.11). In this way, 1 kg of methane corresponds to around 1.11 kg of natural gas.

The methane content in CO_2-based natural gas is 97.41 % (Müller et al. 2011). In this way, 1 kg of methane corresponds to around 1.03 kg of CO_2-based natural gas.

Section 2: CO_2-based basic chemicals

Capturing CO_2 is the first step of the process chain inside the system boundary. The required heat is either supplied by the cement, lignite-fired power or waste incineration plant or by recovery from exothermic methanation or methanol synthesis, respectively. If heat requirement for capturing CO_2 is not satisfied by one of the mentioned heat sources, natural gas serves as fuel for heat generation. In contrast to methanation and methanol synthesis, endothermic steam reforming requires heat and serves not as heat source.

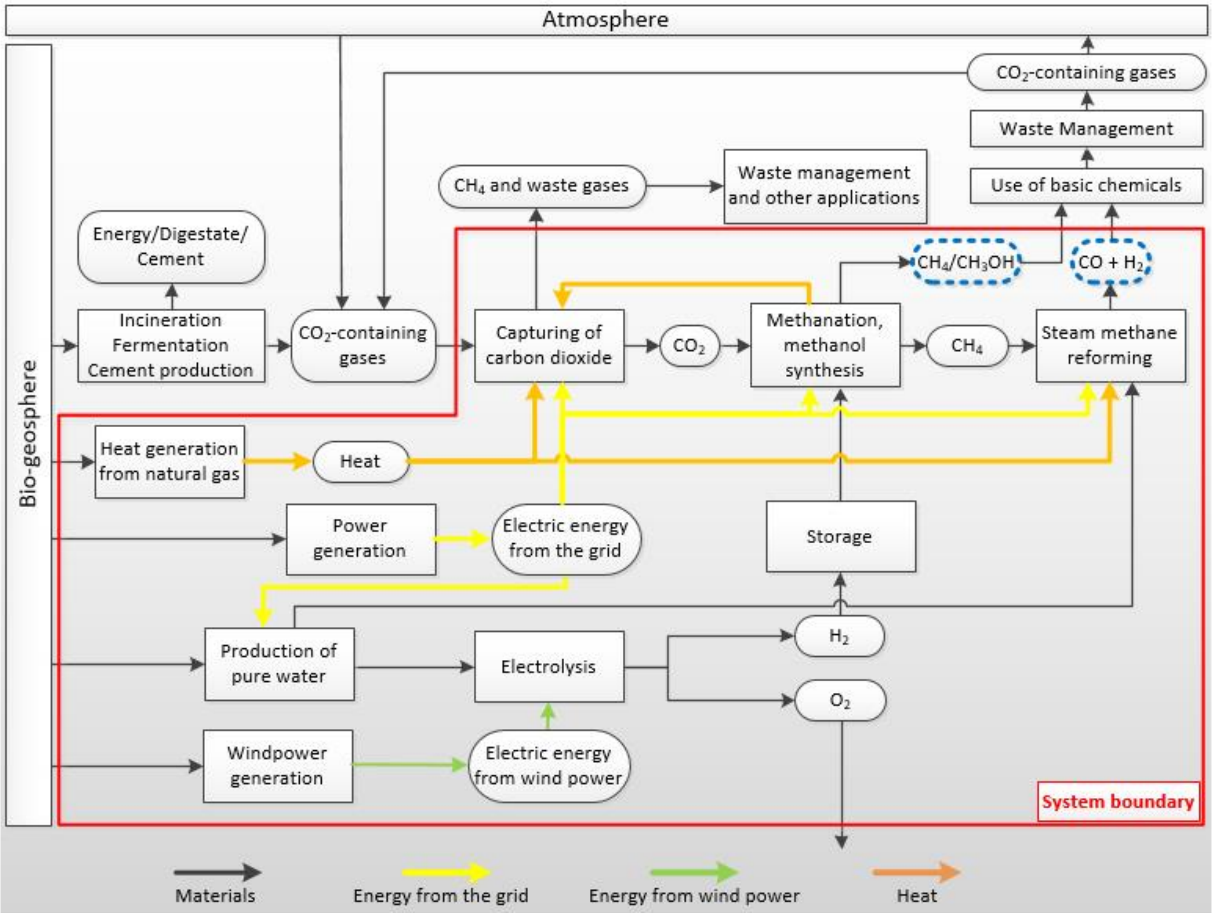


Figure 51 - Production of CO2-based basic chemicals (dashed line).

Section 3: Conventionally produced basic chemicals

For the conventional production of basic chemicals, methane is extracted from bio-geosphere. Nevertheless, the production of synthesis gas and methanol from methane is equivalent to the CO_2-based production.

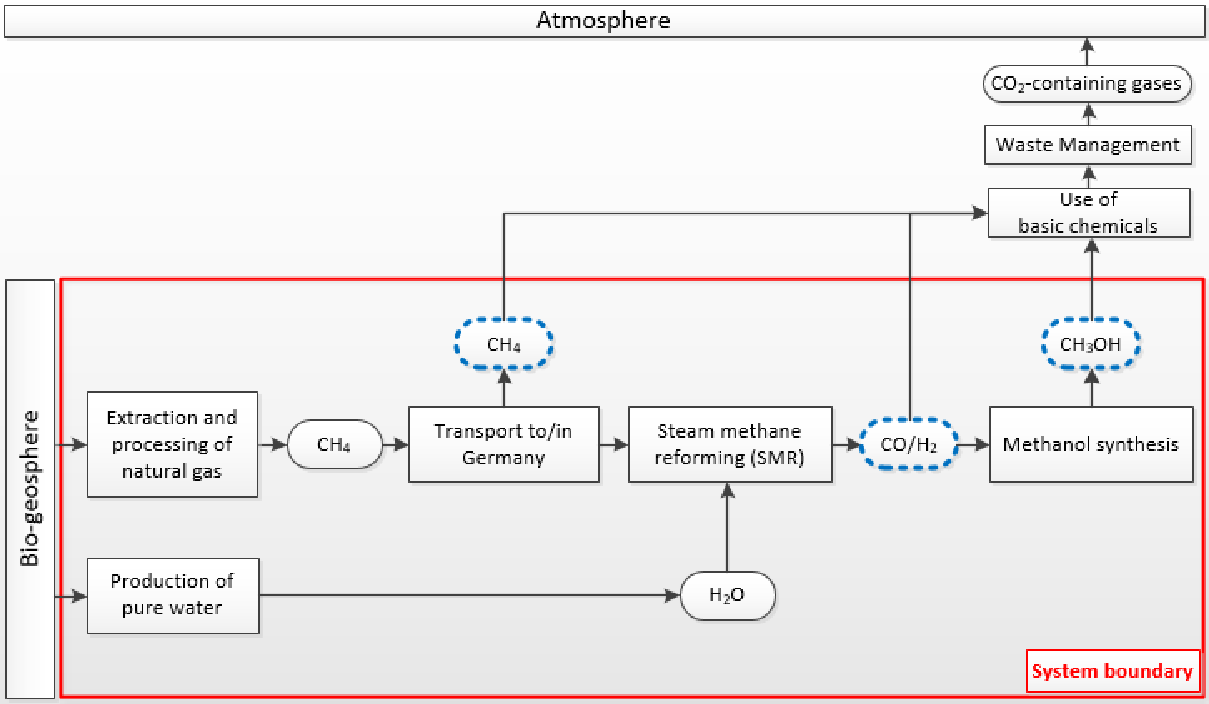


Figure 52 - Conventional production of basic chemicals (dashed line) from natural gas.

Section 4: CO_2-based polymers

The CO_2-based methanol production is the basis for the production of CO_2-based polymers. Formaldehyde is the intermediate for POM production. The production of CO_2-based olefins via MTO is the key element of polyolefin production due to the generation of the double bond of olefins (figure S3).

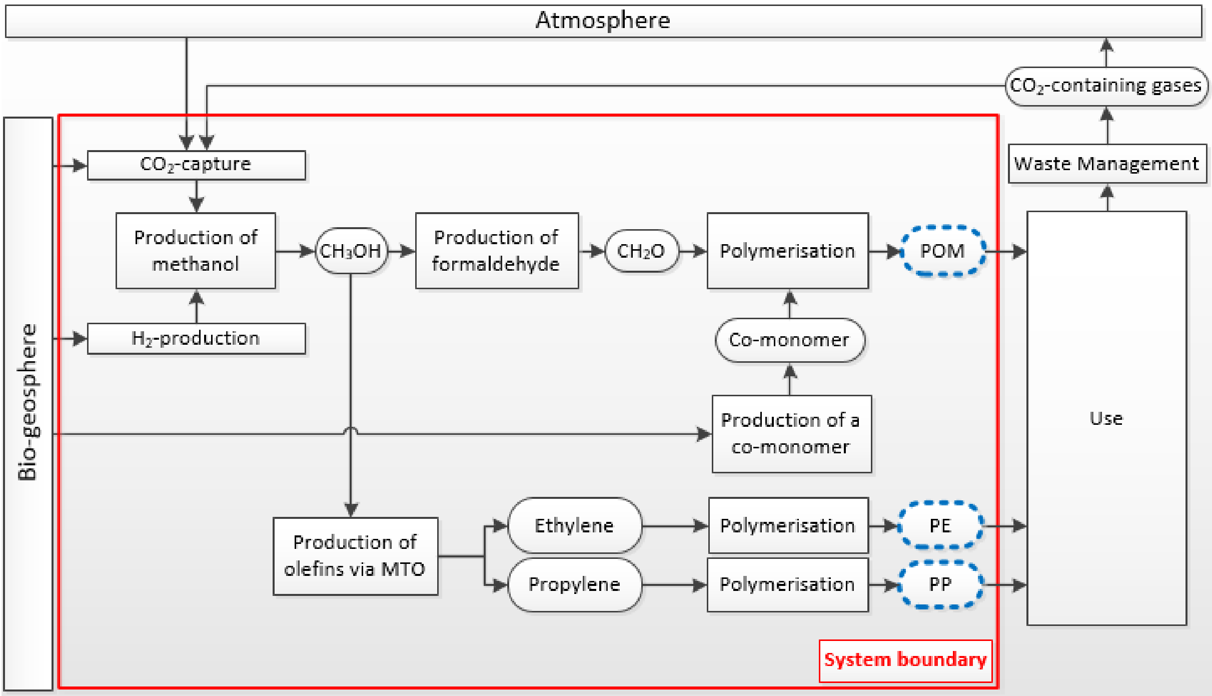


Figure 53 - CO2-based production of POM, PE, and PP (dashed line).

Section 5: Conventionally produced polymers

Except for methane production, the conventional POM production is equivalent to the CO_2-based production. The conventional PE and PP production is completely different to the CO_2-based production as these process chains are not based on MTO but on cracking of petroleum.

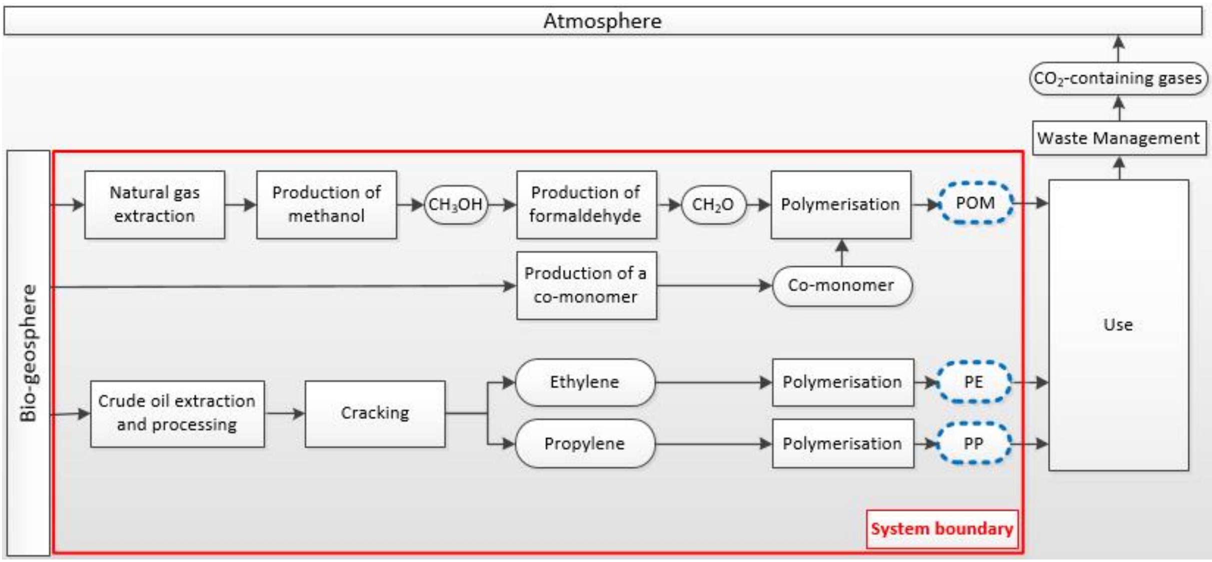


Figure 54 - Conventional production of POM, PE, and PP (dashed line).

Section 6: Life cycle inventory data

The life cycle inventory table provides an overview of the most relevant data. We used ecoinvent 3.1 for all background data.

Table 22 - Life Cycle Assessment Inventory (LCAI) Data

Process		Amount	Unit	Source
CO_2 capturing				
Capturing CO_2 from waste incineration plants		0.237	$kWh_{elec.}$/kg CO_2	Rochelle et al. (2011)
Capturing CO_2 from biogas	for methane	0.114	$kWh_{elec.}$/kg CO_2	MT-Biomethan GmbH (2012)
	for methanol	0.114	$kWh_{elec.}$/kg CO_2	MT-Biomethan GmbH (2012)
		0.571	$kWh_{therm.}$/kg CO_2	MT-Biomethan GmbH (2012)
Capturing CO_2 from lignite-fired power plants		0.164	$kWh_{elec.}$/kg CO_2	Rochelle et al. (2011)
Capturing CO_2 from air	for methane	0.250	$kWh_{elec.}$/kg CO_2	Wurzbacher (2014)
		0.726	$kWh_{therm.}$/kg CO_2	Wurzbacher (2014)
	for methanol	0.250	$kWh_{elec.}$/kg CO_2	Wurzbacher (2014)
		1.650	$kWh_{therm.}$/kg CO_2	Wurzbacher (2014)
Capturing CO_2 from cement plant	for methane	0.020	$kWh_{elec.}$/kg CO_2	Element Energy Ltd. et al. (2014)
	for methanol	0.020	$kWh_{elec.}$/kg CO_2	Element Energy Ltd. et al. (2014)
		0.763	$kWh_{therm.}$/kg CO_2	Element Energy Ltd. et al. (2014)
Electrolysis				
Electricity		54.727	$kWh_{elec.}$/kg H_2	BTS et al. 2014 & Hotellier (2014)
Water		8.921	kg/kg H_2	BTS et al. 2014 & Hotellier (2014)
Chemical Production				
Methanation	Captured CO_2	2.750	kg CO_2/kg methane	Müller et al. (2011)
	Hydrogen	0.520	kg H_2/kg methane	Müller et al. (2011)
	Electricity	0.335	$kWh_{elec.}$/kg methane	Müller et al. (2011)
Methanol synthesis	Captured CO_2	1.374	kg CO_2/kg methanol	Rihko-Struckmann et al. (2010)
	Hydrogen	0.189	kg H_2/kg methanol	Rihko-Struckmann et al. (2010)
	Electricity	1.271	$kWh_{elec.}$/kg methanol	Rihko-Struckmann et al. (2010)
Synthesis gas	Methane	0.471	kg methane/kg syngas	BTS et al. (2014)

Process		Amount	Unit	Source
production	Water	0.529	kg H_2O/ kg syngas	BTS et al. (2014)
	Electricity	0.713	$kWh_{elec.}$/kg syngas	BTS et al. (2014)
	Heat	1.956	$kWh_{therm.}$/kg syngas	BTS et al. (2014)
MTO (Ethylene production)	Methanol	2.571	kg methanol/kg ethylene	Xiang et al. (2014)
	Electricity	0.458	$kWh_{elec.}$/kg ethylene	Xiang et al. (2014)
	Heat	1.552	$kWh_{therm.}$/kg ethylene	Xiang et al. (2014)
MTO (Propylene production)	Methanol	2.571	kg methanol/kg propylene	Xiang et al. (2014)
	Electricity	0.458	$kWh_{elec.}$/kg propylene	Xiang et al. (2014)
	Heat	1.552	$kWh_{therm.}$/kg propylene	Xiang et al. (2014)
Polymerization of ethylene	Ethylene	1.015	kg ethylene/kg PE	Keim (2006)
	Cooling Water	170.000	kg H_2O/kg PE	Keim (2006)
	Butene	0.015	kg butene/kg PE	Keim (2006)
	Electricity	0.450	$kWh_{elec.}$/kg PE	Keim (2006)
	Steam	0.400	kg steam /kg PE	Keim (2006)
Polymerization of propylene	Propylene	1.020	kg propylene/kg PP	Keim (2006)
	Cooling Water	85.000	kg H_2O/kg PP	Keim (2006)
	Electricity	0.330	$kWh_{elec.}$/kg PP	Keim (2006)
	Steam	0.200	kg steam/kg PP	Keim (2006)
Conventional POM production		Not specified (black box process)		Plastics Europe (2011)

<u>Section 7: Modifications of process data compared to ecoinvent 3.1</u>

We exchanged some processes in the Open LCA calculations because we detected some inconsistencies in the ecoinvent database. This leads to a lower material intensity. The table provides an overview of the changed processes and flows in ecoinvent 3.1.

Table 23 - Modified processes in ecoinvent 3.1

Process name	Modification		Comment
	Flow	Correction	
ferronickel production, 25% Ni, cut-off, U - GLO	Nickel, 1.98% in silicates, 1.04% in crude ore, in ground	0.4348 kg instead of 1.7426 kg	Input of nickel is too high; we changed the input flows in accordance with Saurat and Ritthoff (2013)
	Iron, 46% in crude ore, in ground	1.3043 kg instead of 0.0 kg	
aluminium hydroxide production, cut-off, U – GLO	Bauxite, without water - GLO	1.2599 kg instead of 2.53 kg	The input of bauxite in “aluminium hydroxide production” exceeds the stoichiometric value twice and leads to an excessive material intensity; we halved the input of bauxite accordingly
copper mine operation, cut-off, U - RER	Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	0.35 kg instead of 0.2157 kg	The input of copper into “copper concentrate production” is too low and leads finally to a understoichiometric raw copper input for copper products; we adopted data from Schüller et al. (2008) (see also notes in “copper production, primary”)
copper mine operation, cut-off, U - RoW	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	0.35 kg instead of 1.36 kg	The input of copper into “copper concentrate production” is too high and leads finally to a overstoichiometric raw copper input for copper products; we adopted data from Schüller et al. (2008) (see also notes in “copper production, primary”)
copper production, primary, cut-off, U – all regions	electricity, high voltage (input)	1.0445 kWh	The input and output data of primary copper production in ecoinvent 3.1 are inconsistent and out-of-date. We used input (electricity and heat requirements) and output values (Carbon dioxide (CO_2) and Sulfur dioxide (SO_2) emissions) from Schüller et al. (2008). In this way, we assumed a domestic (German) copper production of 32.55 % and a foreign (Chilean) production of 67.45 % (BGR 2015) and weighted the
	Heat, district or industrial, natural gas; Heat, district or industrial, other than natural gas (input)	5.1631 MJ	
	Carbon dioxide, fossil (output)	0.3588 kg	

	Sulfur dioxide (output)	0.2318 kg	values for energy input as well as CO_2 and SO_2 output. Moreover, the emissions of SO_2 were lowered by 17 %, in order to account for the share of the hydrometallurgical production route (no SO_2-emissions) in worldwide copper production (Deutsches Kupferinstitut 2006).

4.3.6 Supporting Information on evaluated LCA’s from literature

Description of considered paramters for the Sunfire process

Table 24: Parameters for the combination of the "fuel 1" and DAC as stated in Universität Stuttgart (2015). GE=German

	Parameter	Fuel 1 & DAC natural gas	Fuel 1 & DAC waste heat
Fuel 1 – Buildings and reactors	Construction, dismantling of the building and the refinery components	Considered	
	Maintenance of the refinery components	Not considered	
Operation of fuel 1	Specific gas torch power [kW]	0.75	
	Operating hours [h/a]	8,000	
	Plant lifetime [a]	20	
	Efficiency of the fuel 1 [%]	65	
	Electricity supply	GErman grid mix, GE hydropower, GE photovoltaics, GE **wind power**	
CO_2-Source	CO_2 from atmosphere via DAC		
Operation DAC	Electricity supply	Same source as for the fuel 1	
	Thermal energy supply	Natural gas	Waste heat
Output	Fuel [MJ]	1	

5. Appendix Task 2

This appendix includes the list of instruments analysed as part of Task 2.1 but which are not included in the main body of the report. All of these instruments are considered relevant for one or more of the CCU routes included in the shortlist. However, there were no observed hurdles to CCU deployment in these policies and they were not identified as core to the analysis. They are included here for the sake of completeness.

5.1 Directive 2001/42/EU on the assessment of the effects of certain plans and programmes on the environment (Strategic Environmental Assessment - SEA)

Being adopted 27 June 2017, the Strategic Environmental Assessment (SEA) Directive implemented a procedure that ensures that the environmental implications of decisions are taken into account before the decisions are made. An important feature of this is public consultation. Environmental assessment can be undertaken for individual projects, such as a dam, motorway, airport or factory subject to Directive 2011/92/EU or for public plans or programmes subject to Directive 2001/42/EC.

The SEA Directive establishes rules for the contribution of the integration of environmental considerations into the preparation and adoption of plans and programmes, by ensuring that, in accordance with this Directive, an environmental assessment is carried out of certain plans and programmes which are likely to have significant effects on the environment, c.f. Article 1. The SEA Directive applies to a wide range of public plans and programmes. Pursuant to article 3, an SEA is mandatory for plans and programmes which are subject to preparation/adoption by an authority (public authority) or required by legislative, regulatory or administrative provisions, c.f. Article 2(a), related to i.e. industry, transport, waste management, water management, land use and which set the framework for future development connected to activites subject to environmental impacts assessment under the Directive 2011/92/EU (EIA c.f. Directive 2014/52/EU), c.f. Article 3(2). Thus, it is for the national authorities to carry out a screening, according to a procedure set out in Annex II of the Directive, in order to determine whether the plans/programmes are likely to have significant environmental effects.

The Directives on Environmental Assessment (SEA and EIA) aim to provide a high level of protection of the environment and to contribute to the integration of environmental considerations into the preparation of projects, plans and programmes with a view to reduce their environmental impact. The common principle of both Directives (SEA as well as EIA) is to ensure that plans, programmes and projects likely to have significant effects on the environment are made subject to an environmental assessment, prior to their approval or authorisation. They ensure public participation in decision-making and thereby strengthen the quality of decisions. The projects and programmes co-financed by the EU (Cohesion, Agricultural and Fisheries Policies) have to comply with the EIA and SEA Directives to receive approval for financial assistance. Hence the Directives on Environmental Assessment are crucial tools for sustainable development.

The SEA is currently under review by the EC (EC DG Environment, REFIT Evaluation of the SEA Directive). We have not observed any barriers to the deployment of CCU technologies in general or for the shortlisted technologies in the SEA.

5.2 Directive No 2011/92/EU on the assessment of the effects of certain public and private projects on the environment (EIA)

The Environmental Assessment (EIA) Directive was adopted 13 December 2011, implementing requirements to assess public and private projects which are likely to have significant effects on the environment.[165] Such assessments can be necessary in order for each Member State to give authorisation and financing to individual projects. The EIA directive follows assessments under Directive No 2001/42/EC (SEA). If the assessments rise simultaneously under both directives *"Member States should be able to provide for coordinated and/or joint procedures fulfilling the requirements",* c.f. Recital (37) Directive 2014/52/EU.

According to Article 4(1) projects listed in Annex I of the Directive shall be made subject to an assessment.

Article 4(2) authorises Member States to determine whether projects listed in Annex II shall be made subject to an assessment. The Member States may decide to require an assessment on either a case-by-case examination or thresholds or criteria set by the Member State. *"Quarries and open-cast mining where the surface of the site exceeds 25 hectares, or peat extraction, where the surface of the site exceeds 150 hectares"* are i.e. obliged to undergo an EIA, c.f. Annex 1 (19) c.f. art. 4 (1), c.f. Directive 2014/52/EU.

Integrated chemical installations are subject to an obligation to do an EIA, c.f. Annex I (6). The same goes for quarries and open-cast mining (c.f. Annex I (18)), installations for storage of chemical product (c.f. Annex I (21)), and any change to or extension of such projects (c.f. Annex I (24)). These paragraphs and obligations comprise several of the technologies studied in this project and identified in the final shortlist, as e.g. mining for silicate minerals (Olive, Serpentine, Wollastonite and Basalt) to produce calcium carbonate or for the production of most of the bulk chemicals. Thus, prior to engaging in the production of the products included in the shortlist, the producer needs to investigate the need for and EIA and potentially perform one.

Finally, it is worth noting that the requirement to do an EIA also applies to installations for the capture of CO_2 streams for the purposes of geological storage pursuant to Directive No 2009/31/EC from installations covered by the Annex, or where the total yearly capture of CO_2 is 1,5 megatonnes or more, c.f. Annex I (23). In general, this would exempt all the technologies on the list as the purpose of the capture is not to store it. However, if the amount of captured CO_2 to be used as input or material in the production of products or energy exceeds 1,5 megatonnes a year, the operations would be subject to the obligation regardless.

A number of other processes and installations, like e.g. the extraction from quarries, open-cast mining and peat extraction (projects not included in Annex I), underground mining, industrial installations for the production of electricity, installations for the manufacture of cement, treatment of intermediate products and production of chemicals etc., are comprised by Annex II and is therefore subject to potential national requirements.

The obligation to carry out an EIA would in general not be perceived as a barrier to deploy a technology. Further, this obligation will not apply to CCU technologies while other competing technologies are exempted. If anything should be labelled as a potential hurdle, it would be the national implementation of the requirements. One technology or process that might be subject to an EIA in one Member State might be exempted in another one. This potential inconsistency is however not a hurdle to the technology in general but might potentially be a hurdle for the flow of people and products across borders in the EU.

[165] Other EU legislation also contain such requirements; e.g. the Water Framework Directive (WFD), or the Industrial Emissions Directive (IED).

As the fulfilment of the obligations under IED lies with each Member State, the different proceedings for assessments reports have not been looked further into.

5.3 Directive No 2000/60/EC establishing a framework for Community action in the field of water policy

The increasing demand by citizens and environmental organisations for cleaner rivers and lakes, groundwater and coastal beaches is one of the main reasons water protection is one of the priorities of the EU (EC DG Environment, Introduction to the new EU Water Framework Directive).The Water Framework Directive (WFD), being adopted 23 October 2000, is an important and operational part of the European Water Policy and was established to protect inland surface waters, transitional waters, coastal waters and groundwater, c.f. Article 1. A tool used to achieve an improvement of water quality is the obligation for Member states to establish environmental quality standards for waters in their territory. The aim of the provisions of the WFD is to achieve *"good ecological potential and good surface water chemical status"* at the latest 15 years after the directives entry into force, c.f. Article 4 (1)(a)(iii). *"Good surface water chemical status"* refers to *"the chemical status achieved by a body of surface water in which concentrations of pollutants do not exceed the environmental quality standards established in Annex IX and under Article 16(7)",* c.f. Article 2 (2).

The WFD provides for a performance-based set of guidelines for the Member States on how to achieve these targets and enables the Member States to implement a framework suitable to local conditions pursuant to the directive. This framework shall incorporate the principles laid down by e.g. the Environmental Impact Assessment Directive as analysed in section [5.2], c.f. the WFD Annex VI. Further, the WFD establishes that the "European Parliament and the Council shall adopt specific measures to prevent and control groundwater pollution", c.f. Article 17 (1). A result of this provision, is the Groundwater Directive, as described in section [5.4] below.

The Member States may authorise injection of water containing substances resulting from mining activities *"into geological formations from which hydrocarbons or other substances have been extracted or into geological formations which for natural reasons are permanently unsuitable for other purposes",* c.f. Article 11. Such permits will subject to the same provision be subject to the environmental quality standards established by the Member State and potential special conditions also specified by the Member State.

The WFD is built on a polluter pays principle (c.f. Recital (11)) and to the extent any of the shortlisted technologies result in pollution of the inland surface waters, transitional waters, coastal waters and groundwater, the owner of the process would be liable for cleaning up or reversing (c.f. Recital (26)) the pollution to the extent possible, reducing impact of the pollution (c.f. Recital (39)) and paying potential damages (c.f. Recital (38)).

The WFD requires however that *"[c]ommon environmental quality standards and emission limit values for certain groups or families of pollutants should be laid down as minimum requirements in Community legislation*", c.f. Recital (42), implying that the directive authorises potential special conditions and restrictions for potential pollutants involved in CCU. We refer to the other sections of this regulatory analysis for more details on these requirements. Further, the WFD requires that *"[p]ollution through the discharge, emission or loss of priority hazardous substances must cease or be phased out,"* c.f. Recital (43), implying that to the extent any CCU processes involve the use of "priority hazardous substances", these substances would need to be replaced.

The WFD includes an Annex VIII on main pollutants, that may be subject to specific restriction. Also, there is an Annex X for *"priority substances".* Annex X is later amended two times, latest by Directive No 2013/39/EU. Directive No 2008/105 provides for environmental quality standards for priority substances and other pollutants provided for in Article 16 of WFD. As far as we have observed, none of the substances included in these Annexes are comprised in the shortlisted technologies. However, it has fallen outside the scope of Task 2 to do an independent investigation of the technologies to map the substances included. Thus, we have not found that there are specific requirements or restrictions in the WFD that would prose a direct barrier to any of the shortlisted technologies. We have further not identified any of these substances as identified in complementing directives in the shortlisted CCU Routes.

As the WFD is imposing administrative burdens on the Member States and the Member States are subject to the restrictions and criteria for establishing plans, monitoring and reporting, the directive does not seem to establish direct burdens on the industry itself. The restrictions and potential barriers would potentially be found in the national framework implemented pursuant to the provisions in the directive.

5.4 Directive No 2006/118/EC on the protection of groundwater against pollution and deterioration (WD)

The Groundwater Directive (GWD) was adopted 12 December 2006 and is established as a subsequent directive to the WFD to prevent and control groundwater pollution, providing specific measures referred to in the Water Framework Directive Article 17 (1) and (2) to prevent groundwater pollution, in particular criteria for the assessment of good groundwater chemical status and *"the identification and reversal of significant and sustained upward trends and for the definition of starting points for trend reversals",* c.f., Article 1. Further, the GDP contains provisions for limiting or preventing inputs of pollutions into groundwater, as well as prevention of deterioration for the status of bodies of groundwater.

Provided the shortlisted technologies do not comprise any of the listed substances in Annex II Part B, we have not found any barriers in the GWD or the subsequent Directive No 2014/80/EU, amending the GWD Annex II on threshold values for groundwater pollution. Our preliminary assessment has not resulted in any limitations for the shortlisted technologies in GWD. Task 2 has, however not performed a full due diligence of the shortlisted technologies' detailed contents of substances as this directive was considered not to be in the core of the scope of work.

5.5 Directive No 2004/35/EC on environmental liability with regard to the prevention and remedying of environmental damage

On 21 April 2004, the European Parliament and the Council of the EU adopted the Environmental Liability Directive (ELD), which has the overall ambitious objective to establish a common European framework of environmental liability for damage to air, water, land, protected species, and natural resources. The ELD is based on "the polluter-pays" principle, c.f. Article 1. The principle is based on the notion that *"an operator whose activity has caused environmental damage or the imminent threat of such damage is to be held financially liable"*, to incentivise an industry to avoid environmental damages, c.f. Recital (2). Environmental damage is defined in this ELD as damage to protected species and natural habitats (c.f. Article 2(a)), water (c.f. Article 2(b)) and land (c.f. Article 2(c)), c.f. Directive 2000/60/EC Article 2(1)(b)).

The ELD deals with the "pure ecological damage", which is based on the powers and duties of public authorities as distinct from a civil liability system for "traditional damage" (damage to property, economic loss, personal injury) (EC DG Environment, Environmental Liability). The ELD applies to all activities listed in *"Annex I of Directive No 96/61/EC with the exception of installations or parts of installations used for research, development and testing of new products* *and processes",* Annex III c.f. IED.[166] Thus, for many of the shortlisted technologies the operator will be subject to the provisions of ELD. E.g. the ELD applies to *"waste management operations, including the collection, transport, recovery and disposal of waste and hazardous waste, including the supervision of such operations and after-care of disposal sites, subject to permit or registration"*, c.f. Article 15 Directive 2006/21/EC

Subject to the ELD, the Member States are obligated to implement a framework subjecting the operator to e.g. take preventive action (c.f. Article 5), remedial action c.f. Article 6), a duty to identify and submit potential remedial measures to the competent approval for approval (c.f. Article 7), and an obligation to bear the costs for the preventive and remedial actions taken pursuant the Directive (c.f. Article 8). However, we have not observed any specific barriers to CCU deployment under ELD as the polluter pays principle applies to a wide range of industries and it can hardly be a valid argument for the operator to claim liability for damage resulting from the production of materials and products as identified in the shortlist. Also, as this Directive falls outside the main scope of work, we have not analysed the ELD in more detail for Task 2.1.

5.6 Directive No 2006/21/EC on the management of waste from extractive industries

The Directive on the management of waste from extractive industries was adopted 15 March 2006 and is part of EUs overall policy on waste management and complements the WFD by providing performance-based guidelines and requirements for the Member States to establish waste management plans (c.f. Article 5) that prevents harm to and adverse effects on water, air, soil, fauna and flora and landscape (c.f. Article 4, c.f. Article 1). This directive provides for *"measures, procedures and guidance to prevent or reduce as far as possible any adverse effects on the environment and any resultant risks to human health, brought about as a result of the management of from the extractive industries"*, c.f. Article 1.

Article 2(1) defines what extractive industries are being subject to the Directive, namely the *"management of waste resulting from the prospecting, extraction, treatment and storage of mineral resources and the working of quarries".* This implies that for the shortlisted technologies with additional mining, this Directive is relevant. Management of waste have to be based on best available techniques (BAT), c.f. Article 4(3), subject to the Industrial Emissions Directive as described and analysed in section [3.4.14] above. For the sake of good order, this does not relate to the assessment of whether the CCU technology itself may be considered as BAT. The BAT refers to the waste management from the extractive industries, while for the shortlisted technologies the silicate minerals (Olivine, Serpentinge, Wollastonite and Basalt) being extracted or accessed through the mining processes were identified as feedstock for the mineralisation process The Directive subjects the Member States to ensure that operators establishes a waste management plan, c.f. Article 5(1).

The Directive further contains provisions for waste facilities, which in relation to this Directive means *"any area designated for the accumulation or deposit of extractive waste, whether in a solid or liquid state or in solution or suspension, […]", c.f. Article 3(15).* A waste facility needs to apply for a permit to operate, c.f. Article 7(1). Neither the requirement to establish a waste management plan or the guidelines and requirement applicable for the waste facilities would differ much from other instruments analysed as part of Task 2. There are a lot of performance-based standards and requirements, with an established baseline.

[166] As we have dealt with in previous sections, Directive No 96/61/EC is repealed by Directive No 2008/1/EC, which further is repealed by Directive No 2010/75, also known as the Industrial Emissions Directive.

Regarding the waste from mining the operator falls under strict liability (no need to proof fault), c.f. the wording *"to any imminent threat of such damage occurring by reason of any of those activities, whenever the operator has been at fault or negligent"* of Article 15, c.f. Article 3 (1) b and Annex III of Directive No 2004/35/EC. Although this might seem onerous for the operator of the mining industry and may be interpreted to be a burden or even a barrier, this liability is not special for the shortlisted technologies and may even be found in a range of other industries with high potential for pollution and damage to the environment and human health, like e.g. the petroleum industry, c.f. Article 3, c.f. Annex III of Directive No 2004/357EC.

The Commission has adopted by Comitology the following implementing measures subject to Article 22 (1):

- Commission Decision No 2009/337/EC on the Criteria for the classification of waste facilities in accordance with Annex III;
- Commission Decision No 2009/335/EC on the Technical guidelines for the establishment of the financial guarantee;
- Commission Decision No 2009/360/EC completing the technical requirements for waste characterisation;
- Commission Decision No 2009/359/EC on the Definition of inert waste in implementation of Article 22 (1)(f); and
- Commission Decision No 2009/358/EC on the Harmonisation, the regular transmission of the information and the questionnaire referred to in Articles 22(1) (a) and 18.

We have not observed any specific barriers to the deployment of CCU technologies in Directive No 2006/21.

5.7 Directive No 2012/18/EU on the control of major-accident hazards involving dangerous substances

Directive No 2012/18/EU on the control of major accident hazards involving dangerous substances, also known as the "Seveso-III", was adopted 4 July 2012. Seveso is the name of an Italian town, which experienced a catastrophic accident in 1976 in a small chemical manufacturing plant, resulting in exposure of dangerous chemicals to residential populations. The accident resulted in the adaptation of legislation to prevent and control such accidents, like Directive No 82/501/EEC (also known as the "Seveso Directive"). The Seveso Directive has later been amended by Directive No 96/82/EC (Seveso II) and finally Directive No 2012/18/EU in order to take into consideration experience from other accidents and developments in EU legislation (EC DG Environment, Major Accidents Hazards).

As the full name of this Directive indicates, it lays down rules for the prevention of major accidents which involve dangerous substances, c.f. Article 1. Seveso III applies to more than 12 000 industrial establishments in the EU where dangerous substances are used or stored in large quantities, mainly in the chemical and petrochemical industry, as well as in fuel wholesale and storage (incl. LPG and LNG) sectors (EC DG Environment, Major Accidents Hazards).

The Directive imposes on the Member States to ensure that the operators of activities and facilities *"take all necessary measures to prevent major accidents and to limit their consequences for human health and the environment"* (c.f. Article 5(1)), which includes amongst other things an obligation to produce a *"major-accident prevention policy"* (c.f. Article 8(1), provide "safety reports" (c.f. Article 10(1), establish "internal emergency plans" (c.f. Article 12(1)), provide information to the public (c.f. Article 14(1) etc. These provisions do not imply a prohibition to produce, buy or store dangerous substances as such. However, precaution needs to be taken and focus is on the establishment of internal emergency plans and accident prevention policies, providing the Member States with the flexibility to implement a performance based national framework.

Annex I of the Directive lists dangerous substances, which are subject to qualifying quantities and refer back to the purpose of the Directive. Not having full knowledge or insights into the detailed contents of each CCU Route, our initial analysis of this Directive may not have uncovered all of the substances involved in the technology routes which would be subject to potential restrictions. E.g. not having detailed knowledge of the properties of synthetic fuels, our observation is that the fuels may be comprised by the wording *"alternative fuels serving the same purposes and with similar properties as regards flammability and environmental hazards as the products referred to in points (a) to (d)",* c.f. Annex I (34). However, knowing that gasolines and naphthas, kerosenes (including jet fuels), gas oils (including diesel fuels, home heating oils and gas oil blending streams) and heavy fuel oils are all subject to the same provision, c.f. (a)-(d), and further that these products are available on the market, we have not concluded this inclusion represents any potential barriers to synthetic fuels as such. A more recognisable case of inclusion is Methanol, c.f. Annex I (22). The inclusion of the substance does however not imply a prohibition to produce or buy it, c.f. the analysis above. The requirements apply to a wide range of industries and activities and we have not observed specific restrictions for CCU. We have not observed any barriers to the deployment of CCU technologies amongst the general provisions of the Directive.

5.8 Regulation No 166/2006 concerning the establishment of a European Pollutant Release and Transfer Register

The Regulation on the European Pollutant Release and Transfer Register (E-PRTR) was adopted 18 January 2006 which established a web-based register which implements the UNECE PRTR Protocol, signed in May 2003 in Kiev. In order to simplify EU IED, E-PRTR Regulation subjects Member States reporting of their releases. The register contains information on industrial releases of pollutants to air, water and land, as well as off-site transfers of pollutants present in waste-water and waste and includes information of more than 33 000 facilities in 28 EU countries in addition to Iceland, Liechtenstein, Norway, Switzerland and Serbia.

The register covers 91 pollutants listed in Annex II, including greenhouse gases, other gases, heavy metals, pesticides, chlorinated organic substances and other inorganic substances. The industrial sub-sectors and activities subject to registration are listed in Annex I of the E-PRTR Regulation. Task 2 has not performed an independent review of the shortlisted products or CCU routes to rule out any pollutants comprised by the E-PRTR Regulation. A duty to register activities and substances is however not consider a hurdle in itself and omitting this analysis should therefore not affect the final conclusions of Task 2.1.

5.9 Regulation No 1272/2008/EC on the classification, labelling and packaging of substances and mixtures

The Regulation for the classification, labelling and packaging of substances and mixtures (CLP) was adopted 16 December 2008. When dealing with chemicals, CLP must be taken into account. Classification and labelling identify hazardous chemicals and inform users about their hazards through standard symbols and phrases. The purpose of the CLP Regulation is to ensure a high level of protection of health and the environment, as well as the free movement of substances, mixtures and articles, c.f. Article 1.

Since 1 June 2015, the CLP Regulation is the only legislation in force in the EU for classification and labelling of substances and mixtures (ECHA, Understanding CLP). The regulation implements the United Nations Globally Harmonized System (GHS) for classifying and communicating the hazardous properties of industrial and consumer chemicals. The system has been developed by the United Nations given the expanding international market in chemical substances and mixtures, to help protect people and the environment, and to facilitate trade (EC DG Growth, Classification and Labelling (CLP/GHS).

Obligations on classification, labelling and packaging is not considered a hindrance for the CCU technology routes as such. Therefore, we have not made any further assessment of the specifics of the provisions of this regulation.

6. Appendix: Terms of reference

Identification and analysis of promising Carbon Capture and Utilisation technologies, including their regulatory aspects

1. Context/General information

Carbon capture and utilisation (CCU) refers to a very wide range of technologies that:

- Use CO_2 as a working fluid or solvent such as for enhanced oil recovery;
- Use CO_2 as a feedstock for conversion into value-added products such as fuels, chemicals or building materials.

The latter *conversion* CCU technologies are at different technological readiness, from laboratory testing to commercial demonstration. They could offer a promising avenue for decarbonisation, industrial innovation and competitiveness of energy intensive industries.

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 in the future Innovation Fund[167], inter alia, as one of the technologies and processes for decarbonisation of energy-intensive industries.

However, CCU technologies face a range of environmental, economic, technical and regulatory challenges which need to be carefully considered so that proper incentives are provided to the technologies, which provide actual climate and environmental benefits.

As regards technical challenges, advancement of knowledge is essential to improve the economic feasibility and potential of CCU technologies. Information on the environmental performance of the technologies is currently limited and scattered. Most promising CCU technologies require significant amounts of energy. Their climate mitigation potential, in particular, is dependent on the carbon intensity of the electricity used for the processes, the efficiency of the technologies, the GHG intensity of other inputs, how long the CO_2 stays in its new form, and which products or fuels they replace. As a result, the life cycle analysis can lead to very different results depending on the specific technologies considered. The economic feasibility of CCU technologies also depends on a number of factors, such as the costs of inputs (CO_2, electricity, catalysts, etc.), technological improvements and the price of alternatives.

[167] See Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments (COM/2015/0337 final), http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015PC0337

With regards to the regulatory framework, in the EU ETS the use of CO_2 as a feedstock for conversion into value-added products is treated in the same way as any other emissions, i.e. allowances have to be surrendered, because these conversion CCU technologies do not represent permanent storage as foreseen by (article 12 (3a) of the ETS Directive).

A recent Court judgement[168] dealt with the very specific case of CO_2 transferred outside a lime producing installation covered by the EU ETS and chemically bound in a stable product in the production of precipitated calcium carbonate. The Court found that the transferred CO_2 should not be counted as emissions under the EU ETS. Consideration is now being given to necessary changes to relevant rules in the Monitoring and Reporting Regulation (MRR) and what this means for other climate legislation like the proposed Effort Sharing Regulation and LULUCF Regulation.

The Commission proposal for a revised EU ETS Directive proposes the establishment of an Innovation fund to support innovation in low-carbon technologies and processes in industrial sectors listed in Annex I of the ETS Directive, as well as renewable energy and carbon capture and storage. CCU technologies will be eligible for support under this fund. Once the revision of the EU ETS Directive is adopted, the implementing legislation will lay out in detail the various modalities for support in the different sectors.

Under the Fuel Quality Directive, fuel suppliers can reach their 2020 GHG intensity target by placing on the market novel fuels, including CCU fuels, provided these fuels perform better in terms of GHG intensity. The Commission may adopt GHG intensity default values for this purpose by the end of 2017. Sustainability criteria will also have to be established to determine, which type of CCU fuels can account for reaching the blending mandate proposed under the proposal for a Directive on the Promotion of the Use of Energy from Renewable Sources (recast) (RED II)[169].

2. Subject of the request

This service request aims to build a better understanding of novel CCU technologies with two main sub-objectives: 1) to assess the readiness and map the roll out of different CCU technologies in order to clarify which types of technologies are viable for support, including from the planned Innovation Fund under the EU ETS; 2) to examine the EU regulatory set up related to the technologies concerned and assess whether specific provisions are necessary to reflect the contribution by these innovative technologies to climate mitigation while preserving the environmental integrity of the relevant legislation, and 3) to engage with stakeholders for better understanding of the technologies and the legislative setup.

The contract will gather up to date information on CCU technologies that will become ready for large-scale pre-commercial demonstration in the period 2021-2030. Further insight into the technological progress, environmental impact and economic viability as well as the net benefits of such technologies for the long term decarbonisation of power and industry sectors could help inform preparatory work on appropriate arrangements to provide future support to such technologies through the Innovation Fund. The contract will also provide insights on monitoring and reporting of CO_2 emissions for CCU activities, including through life cycle assessment approaches. All relevant EU climate, environmental and energy legislation will be assessed in respect to these novel technologies, options to address the issues that are identified will be developed and their impact compared.

[168] Judgment of the Court (First Chamber) of 19 January 2017; Schaefer Kalk GmbH & Co. KG v Bundesrepublik Deutschland; Case C-460/15

[169] COM(2016)767, http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52016PC0767R%2801%29

The contractor will build on previous and ongoing studies, literature review, relevant research projects, as well as stakeholder and expert consultation.

Technologies able to convert carbon dioxide or other waste processing and exhaust gases and integrate them in products or fuels will be reviewed. Technologies, which use carbon dioxide directly as a solvent such as for enhanced hydrocarbon recovery, or for a working fluid such as in supercritical CO_2 power cycles are excluded. Technologies, which are already mature and commercial such as use of CO_2 in soft drinks or fire retardants will have to be listed at the start of the project, but will not be part of this service request either.

3. Tasks to be performed

Task 1 "Technologies assessment"

Sub-task 1.1. Technological readiness for large-scale demonstration

The objective of sub-task 1.1 is to identify and assess which CCU technologies are not yet commercially available, but are sufficiently mature in terms of technological development to be ready for demonstration at pre-commercial scale in the period 2021-2030. As part of this assessment, the contractor will gather information on projects under development in the EU and worldwide, including on their technological readiness, the estimated actual climate and environmental benefits, expected time to commercialisation, the technological advancement necessary to make the technologies economically feasible and their expected timescale, the financial gap for large-scale first-of-a-kind demonstration projects, and replication potential. Based on this analysis, the contractor shall identify the most appropriate technologies for potential support under the Innovation Fund and other instruments available at EU level. The contractor will identify possible eligibility and selection criteria, which would be appropriate for these technologies in the context of the Innovation Fund. The contractor will provide an overview of the other EU instruments, which can support these technologies and outline the framework conditions for the support.

Sub-task 1.2. Technical, economic, climate and energy assessment

The objective of sub-task 1.2 is to make a technical, economic and environmental assessment of the technologies identified in sub-task 1.1. The contractor has to identify and quantify the framework conditions that will allow technologies to become competitive and to deliver climate and environmental benefits. For this purpose, the contractor will study a number of technical, economic and environmental questions. The most pertinent questions are described below, but the contractor is encouraged to suggest other relevant aspects and present the most appropriate approach to deliver answers to them.

- The economic conditions that will allow projects to break-even, such as cost and availability of inputs, price of products and alternatives under the current and planned energy and climate policies up to 2030 and with an outlook to 2050.

- Generic lifecycle assessments of example CCU products or fuels should be provided for the main technologies identified under sub-task 1.1. The impact of evolution of key parameters, such as grid carbon intensity, should be shown in the calculations.

- A comparison of CCU products or fuels with the products or fuels they substitute in terms of lifecycle CO2 emissions shall be performed.

- The climate mitigation potential of these technologies in terms of CO2 avoided per sector, per volume of product and overall at EU level under different plausible scenarios of market penetration.

- The CO_2 feedstock is emitted in different volumes, concentrations and purity from power and industrial installations. Some (clusters of) plants may need to be situated next to specific raw materials or feedstocks or integrated with renewable energy plants. What impacts would these and other similar consideration have on potential market penetration?

- The fate of the CO_2 in each different family of products shall be outlined based on existing scientific literature and/or available company information. The aims would be to determine 1) how long the CO_2 can typically be expected to remain in the different final products and under what conditions and 2) how this can be monitored and verified, including through existing methodologies?

- The energy input per volume of CO_2 used and avoided and energy penalty (energy lost in various processes) per product or fuel shall be calculated and compared with alternative products, fuels and solutions.

- The potential of different technologies to serve as energy storage shall be studied, including under what conditions.

<u>Sub-task 1.3. Market barriers, impacts and opportunities</u>

The objective of sub-task 1.3 is to identify and estimate in general terms other economic benefits that these technologies may deliver, but also potential market barriers and also negative impacts from their application. This should include:

- Assessing the market conditions and possible barriers for CCU products and fuels;

- Synergies that can be exploited between CO_2 emitters and users in terms of infrastructure at EU and regional level shall be identified, prioritising the technologies where the EU can have a competitive advantage.

- The potential other benefits from development of these technologies, e.g. competitiveness, jobs, SMEs, regional development and cohesion shall be estimated.

- In which sectors the climate mitigation potential of the various CCU technologies would contribute most to reaching the greenhouse gas reduction targets of the EU by 2030 and 2050.

- Implications from deployment should also be assessed especially in terms of the volumes of energy needed or saved in case of RES power curtailment.

- Substantial impacts on other environmental parameters should also be identified, such as water, waste or use of raw materials.

The results should be quantified to the extent possible (or a qualitative assessment can be presented when quantification is not possible) and comparison should be made with alternative technological solutions for the products/services that CCU applications will substitute. The assessment should adopt a system-based approach and consider the transformation of the energy, industry and mobility likely to happen up to 2030, 2040 and 2050.

Task 2 "Regulatory assessment"

Sub-task 2.1. Analysis of the current regulatory setup

Under Sub-task 2.1. the contractor will analyse the current regulatory setup affecting CCU technologies. The Commission proposals for legislation should also be considered. All legislation, which may affect the novel promising technologies identified in sub-task 1.1. shall be analysed. This will cover at least the EU Emissions Trading Scheme Directive and its implementing legislation, the greenhouse gas inventory reporting requirements, the effect of the EJC ruling and links to the benchmarking decision, the Industrial Emissions Directive, the Fuel Quality Directive and the Renewable Energy Directive, Effort Sharing Decision, LULUCF, the CCS Directive, rules governing the internal market for electricity. Other legislation if relevant to CCU technologies must also be considered.

Sub-task. 2.2. Developing options

In this sub-task, the contractor will develop options for addressing the issues identified under sub-task 2.1. The following considerations should be taken into account but the contractor has to address all other identified issues.

Carbon capture and utilisation technologies may be transferring CO_2 emissions from one installation or sector to another and this has to be properly accounted for in the legislation covering different sectors to avoid potential loopholes connected to the transfer of carbon dioxide. The effect on compliance obligations for all actors that are involved, as well as the issuance and surrender of allowances under the EU ETS needs to be taken into account.

The complete, consistent, transparent and accurate reporting of greenhouse gas emissions is fundamental to the effective operation of the EU ETS. Therefore, this issue needs to be addressed, as well as obligations under the UNFCCC. The conditions under which any carbon emissions through the CCU applications concerned could potentially be re-released, or considered to be permanently avoided need to be clarified.

Under this sub-task it should be assessed how to measure and monitor the carbon dioxide in its lifecycle, including identification of existing uncertainties. Approaches for dealing with liabilities for emissions that are released at a different time and place to that of the CCU applications, including accidental releases, shall be assessed.

The contractor should also consider if any specific provisions are needed in related climate legislation, including the Effort Sharing Decision, the proposed Effort Sharing and LULUCF regulations, the FQD (e.g. to accommodate pure CCU fuels or blends of CCU fuels such as methanol with fossil fuels).

Sub-task 2.3. Assessing impacts

Under this sub-task, the contractor shall provide a preliminary assessment and comparison of the options developed under sub-task 2.2. In particular, this shall consider their feasibility for implementation and coherence with the existing legal framework as well as their effectiveness in ensuring the safeguarding of the environmental integrity of the existing framework. In addition, likely, economic and social impacts shall be listed. The effectiveness and efficiency (benefits and costs) of different options shall be compared.

Task 3 "Engagement with stakeholders"

The third task will aim to enrich and crosscheck the findings by seeking input from experts and stakeholders. This will comprise of written consultations and workshops. Two one-day focused workshops shall be organised to take stock with representatives of stakeholders of how best to support the further development of the potentially promising CCU technologies. During these workshops the contractor will discuss the findings of Tasks 1 and 2 with the stakeholders. The workshops should be by invitation only and will aim to focus primarily on the participation of those experts in the field who are directly involved in the development of the technologies concerned within the relevant companies and industries. The lists of invitees and participants should be agreed with the Commission. The contractor should aim at a small but representative and diverse group of experts – between 20 and 30 people - to allow for meaningful discussions.

In addition, the contract would envisage the organisation of one one-day open event, in which a wider audience of interested stakeholders and researchers can attend. The contractor should consult with the Commission on the lists of invitees and participants. The contractor should aim at a representative and diverse group of experts and stakeholders – between 100 and 150 people - to allow for meaningful discussions and dissemination of findings. This final open event will present the findings on Task 1, elements of Task 2 and serve for drawing final conclusions.

EUROPE DIRECT is a service to help you find answers to your questions about the European Union

Freephone number (*):
00 800 6 7 8 9 10 11

(*) The information given is free, as are most calls (though some operators, phone boxes or hotels may charge you)

LEGAL NOTICE

This document has been prepared for the European Commission however it reflects the views only of the authors, and the Commission cannot be held responsible for any use which may be made of the information contained therein.

More information on the European Union is available on the Internet (http://www.europa.eu).

Luxembourg: Publications Office of the European Union, 2019

PDF	ISBN 978-92-76-03401-8	doi: 10.2834/348288	ML-02-19-300-EN-N

HOW TO OBTAIN EU PUBLICATIONS

Free publications:

- one copy:
  via EU Bookshop (http://bookshop.europa.eu);

- more than one copy or posters/maps:
  from the European Union's representations (http://ec.europa.eu/represent_en.htm);
  from the delegations in non-EU countries
  (http://eeas.europa.eu/delegations/index_en.htm);
  by contacting the Europe Direct service (http://europa.eu/europedirect/index_en.htm)
  or calling 00 800 6 7 8 9 10 11 (freephone number from anywhere in the EU) (*).

  (*) The information given is free, as are most calls (though some operators, phone boxes or hotels may charge you).

Priced publications:

- via EU Bookshop (http://bookshop.europa.eu).

ML-02-19-300-EN-N

Publications Office

doi: 10.2834/348288
ISBN 978-92-76-03401-8