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CO_2 as an Asset

Challenges and potential for society

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IASS POTSDAM

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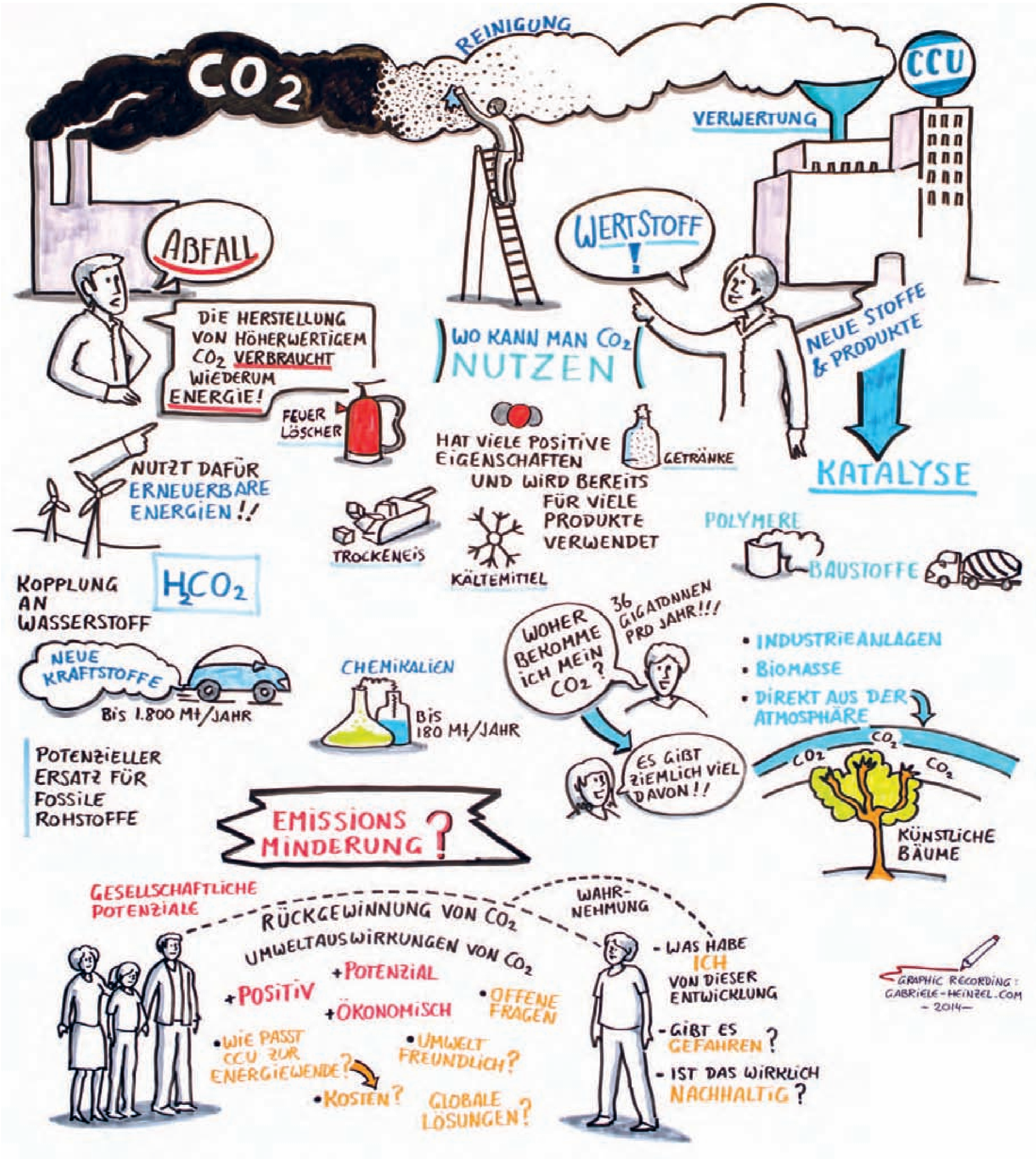
List of Abbreviations

B2B	Business-to-Business
B2C	Business-to-Consumer
BECCS	Bio Energy with Carbon Capture and Storage
BMBF	Bundesministerium für Bildung und Forschung/Federal Ministry of Education and Research
BMWi	Bundesministerium für Wirtschaft und Energie/Federal Ministry for Economic Affairs and Energy
BUND	Bund für Umwelt und Naturschutz Deutschland/Federation for Environment and Nature Protection Germany
CAT	Katalysezentrum/Catalytic Center
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation/Carbon Capture and Use
CCUS	Carbon Capture Utilization and Storage
CDU	Carbon Dioxide Utilisation
Climate KIC	Climate Knowledge and Innovation Communities
CO_2	Carbon Dioxide
CR	Carbon Recycling
CRI	Carbon Recycling International
DIN	Deutsche Industrienorm/German Industrial Standard
DOE	Department of Energy
EGR	Enhanced Gas Recovery
EU ETS	EU Emission Trading System
EOR	Enhanced Oil Recovery
IASS	Institute for Advanced Sustainability Studies
ICCDU	International Conference on Carbon Dioxide Utilization
IF	Europäischer Innovationsfonds/European Innovation Fonds
IGBP	International Geosphere-Biosphere Programme
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
ITMC	Institut für Technische und Makromolekulare Chemie/Institute for Technical an Macromulecular Chemistry
KrWG	Kreislaufwirtschaftsgesetz/Closed Substance Cycle Waste Management Act
LTT	Lehrstuhl für Technische Thermodynamik/Chair of Technical Thermodynamics
NGO	Non-governmental Organisation
PCR	Product Category Rules
PtG	Power to Gas
PtL	Power to Liquids
PtX	Power to X
RWTH	Rheinisch-Westfälische Technische Hochschule Aachen/Technical University Aachen
SCOT	Smart CO_2 Transformation Project
SDG	Sustainable Development Goals
UBA	Umweltbundesamt/Federal Environmental Agency
UWG	Gesetz gegen den unlauteren Wettbewerb/Law against unfair competition
LCSA	Life Cycle Sustainability Analysis
PCR	Product Category Rules



This illustration is a "Graphic Recording" of the dialogue event "Can CO_2 be recycled? A dialogue on Carbon Capture and Utilisation (CCU) Technologies" held on June 5th 2014 at IASS Potsdam. The drawing contains different patterns of argumentation and questions that shaped the discussion. See also chapter 6.

1. Introduction

Carbon dioxide (CO_2) is a fundamental component of all life on Earth. Due to the considerable increase in emissions, particularly industrial emissions, CO_2 has, however, become a waste product and greenhouse gas damaging to the climate and, consequently, a threat to both humanity and nature. For almost 50 years, chemical research has been pursuing the idea of making the CO_2 molecule useful as a raw material (Aresta and Dibenedetto 2010). Within the context of the oil crises of the 1970s, and contingent on the current need for climate protection, there has been a rise in global interest in the research and development of technologies which could make CO_2 useful as a source of carbon. Several regions in Europe, but also in North America and Asia have started sponsorship programmes to support the development of such technologies (BMBF 2014, Climate-KIC 2014, U.S. Department of Energy [DOE] n.d.).

The goal of these efforts is to integrate this climate-damaging gas in extremely diverse industrial production processes as a raw material. The use of CO_2 would not only allow for the production of useful raw materials and products, such technologies could also emulate a natural carbon cycle (Peters et al. 2011). At the same time, they have the potential to reduce the consumption of other fossil resources and, in so doing, they might not only contribute to the extension of the resource base, but also reduce emissions whilst providing protection for natural resources (von der Assen et al. 2013). Technological breakthroughs and advancements are currently observed in carbon capture technologies in the catalysis and transformation of CO_2 (Aresta 2010, Mikkelsen et al. 2010, Peters et al. 2011, Styring et al. 2011, Wilcox 2012, Smit et al. 2014, Klankermayer and Leitner 2015), and the first innovative CO_2-based products are already coming onto the markets.

1.1. About the project

The chemical and technical further development of technologies for the utilisation of carbon dioxide has, in Germany, become widely diversified, made possible, not least, through the comprehensive sponsorship programmes of the Federal Ministry of Education and Research (BMBF 2014) and the existing interest of an industrialised country which lacks raw materials in an additional source of carbon. Currently, the scientific identification, analysis and assessment of the societal potential and challenges associated with this technology is, however, distinguished by a simple lack of the due attention (Jones et al. 2014, Jones and Jones 2016). In the year 2012, therefore, the Institute for Advanced Sustainability Studies (IASS) implemented a project on the topic of "CO_2 as a Recyclable Material – Potential and Challenges for Society"; this project also included the framework for the cooperative project "CO_2ntext" with the project partners RWTH Aachen University (Institute for Technical and Macromolecular Chemistry – ITMC and Professorial Chair for Technical Thermodynamics – LTT) as well as Bayer Material Science which, since 2015, has been working under the name Covestro. The goal of this overlapping project was to consider the non-technological aspects of development of so-called "Carbon Capture and Utilisation" (CCU)-technology – for example the effects on a CO_2 market or the possible reception in the media or by stakeholders – in an interdisciplinary fashion from the perspectives of natural, engineering, economic and communication sciences. The content of the IASS project and the cooperation involved identifying and evaluating the possible challenges and potentials of the existing technology for the environment and society, which could be associated with actual implementation of technology, despite these often being largely still in early stages of development. In this way, parameters were to be developed which would, in particular, serve to adapt as well as potentially further the development of this field of technology to societal sustainability demands (Naims et al. 2015). Within the scope of the cooperation, scientific foundations for such recommendations were to be worked out, an information platform was to be set up, and several stakeholder dialogues were to be implemented.

The research work at IASS occurred on an interdisciplinary and transdisciplinary basis, i.e. involving various disciplines and in constant dialogue and exchange with representatives from science, economy, politics and society at large. It included, in addition, intensive discourse with colleagues from other projects implemented at IASS and was, with regard to content, supplemented with references to other individual disciplinary research questions of the scientists involved.

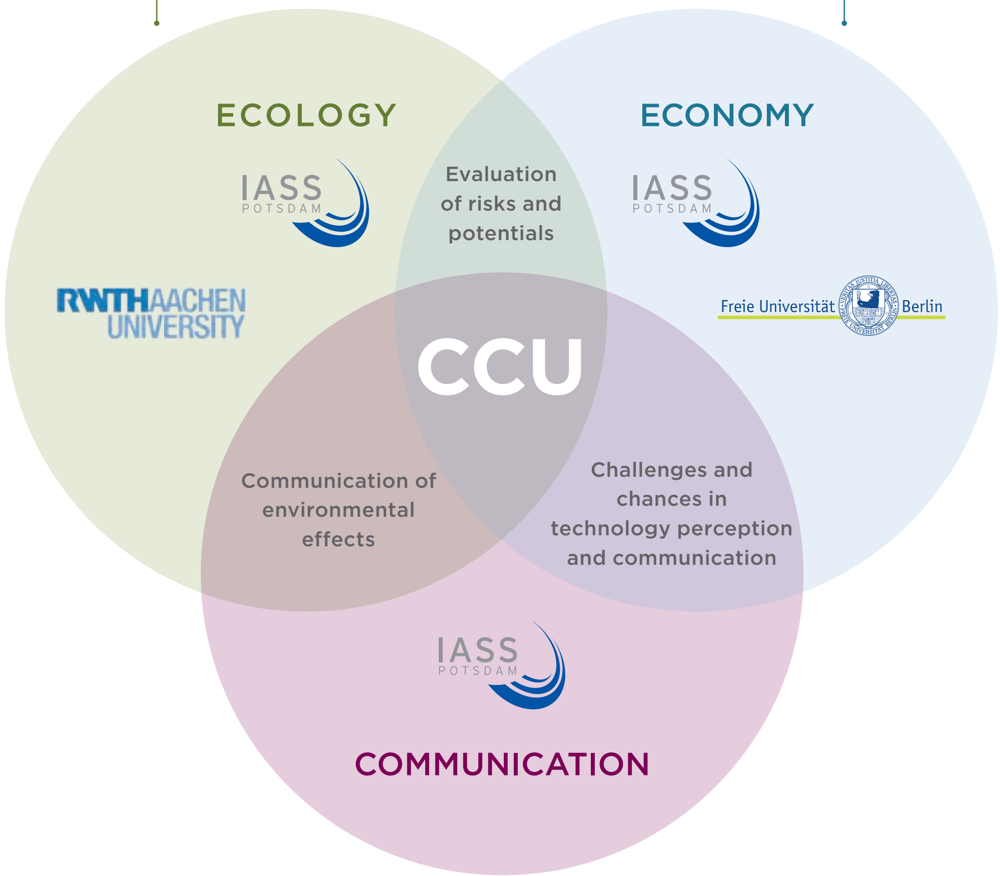
In particular, the partners at the ITMC, the CAT Catalysis Centre and the LTT, as well as at Covestro, brought many years of experience and technical expertise in CCU to the project. With their know-how of chemical-technical aspects as well as their industry-specific knowledge of processes and environmental performance, they took on a consulting role in the interdisciplinary research at the IASS. In so doing, they helped the employees in the individual sub-projects, to develop a fundamental understanding of the technical methods and to build possible products, while also, in joint dialogue, identified open research questions of societal relevance. Due to the fact that the Life Cycle Assessment (LCA) is an important tool for determination and assessment of ecological effects of CCU technology, and thus also a decisive basis for future development and industrial implementation of this technology, there was close cooperation in this area with the LTT of the RWTH Aachen University, which has extensive experience in this field, having already implemented first LCAs of possible CO_2 routes at the beginning of the project.

1.2. About this document

The current final report of the project "CO_2 as an Asset" primarily represents – following a short introduction to CCU technology – a summary of the project results, consisting of the subprojects ecology, economy and communication implemented at the IASS, in addition to important interfacing topics. The research on the topic of LCA was carried out by the IASS Fellow Ana Maria Lorente Lafuente at the LTT of the RWTH Aachen University under the leadership of Prof. André Bardow. In addition, the report offers an overview of the events implemented within the scope of the project, and other dialogue-centred measures. The implications and recommendations for political decision makers which were developed from the work of the project can be found in the sections 8, 9 and 10.

- Life Cycle Analysis (LCA) of CCU (in cooperation with the Chair of Technical Thermodynamics, RWTH Aachen)
- Environmental side effects of carbon capture technologies

- Economic overview on CCU technologies
- Scenario analysis of CO_2 supply and demand
- Analysis of economic effects of CCU (ongoing, PhD project, Freie Universität Berlin)



- Media analysis and expert interviews on CCU perception
- Neutral information material on societal aspects of CCU
- Stakeholder dialogues on CCU
- Regional aspects in the perception of CCU (ongoing study in cooperation with University of Sheffield)

Figure 1: Research on CCU technologies at the IASS

Source: IASS

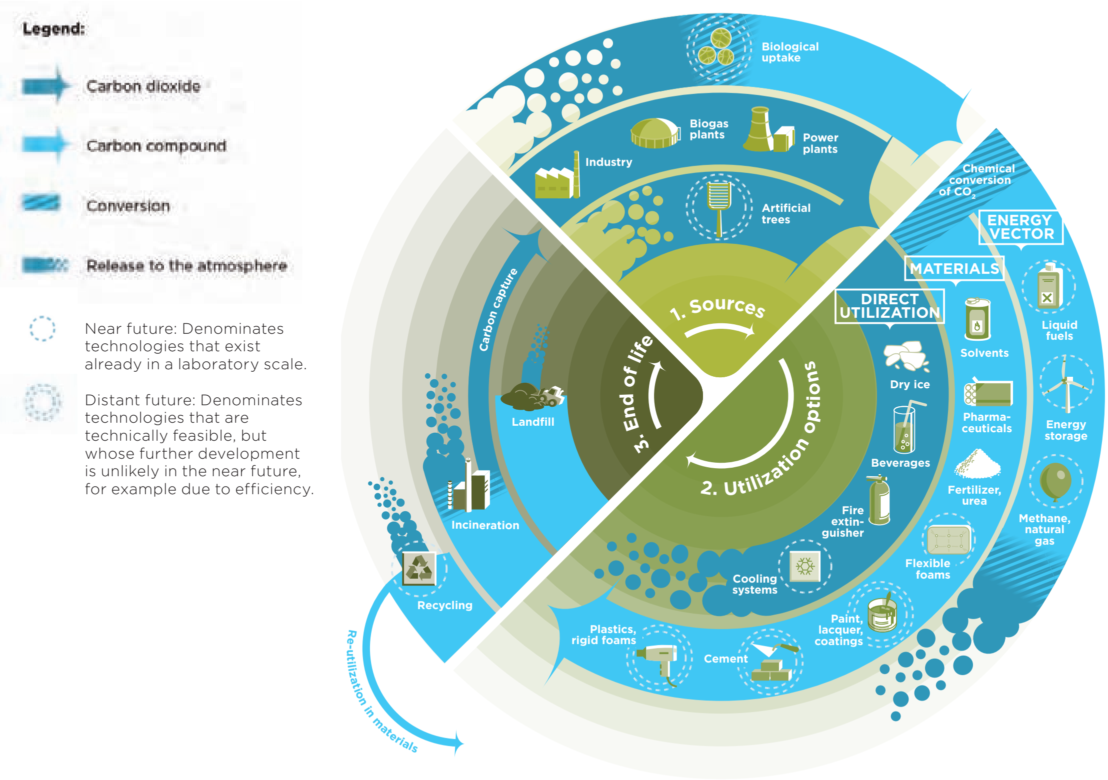


Figure 2: Circular representation of CO_2 utilisation options

Source: IASS, Infographic: Mario Mensch

CCU AT A GLANCE

This circular image was developed within the context of the project work at the IASS. It serves to provide an overview of various elements in diverse CCU processes and can be used as support in dialogues, in particular with laypersons.

The image is sub-divided into sections in temporal order: CO_2 sources, possibilities for use and "End of Life". In the area "possibilities for use", the three central methods of use, 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 mean "in development".

The blue arrows stand for the CO_2 – dark, directly as CO_2; light, transformed carbon dioxide compound; and dotted, as 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 are, in particular, the "end of life" phase with the options incineration, landfill or recycling and (renewed) emission after direct utilisation or utilisation as energy sources.

The image can be viewed on the web page www.co2inside.de and can, at request, be made available for use by the IASS with a link to the originator.

2. A short introduction to the utilisation of carbon dioxide

2.1. CCU processes

The utilisation of carbon dioxide in diverse production processes is referred to as "Carbon Capture and Utilization (CCU)" or "Carbon Dioxide Utilization" (CDU) (Jones et al. 2014) or "Carbon Recycling" (CR) (Bringezu 2014). This refers to technologies and processes which, either directly or following chemical transformation, use carbon dioxide as a component of a carbon dioxide compound in materials or energy sources, thus rendering the carbon dioxide useful. Particularly in the USA, CCU is defined under the heading "Carbon Capture Utilization and Storage" (CCUS) (NSF 2013). CCU processes involve the capture and compaction of carbon dioxide, its transport (if necessary), and the separate functional utilisation of the CO_2 (von der Assen et al. 2013).

Despite commonalities in the possible capture of CO_2 from industrial emissions, CCU differs fundamentally from the so-called "Carbon Capture and Storage" (CCS) technologies. While these, as "end of pipe" technologies, aspire to the durable underground storage of CO_2, Carbon Capture and Utilization (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 (please also refer to Chapter 8).

Given that CO_2 is extremely inert, aids are usually necessary to allow 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 (Peters et al. 2011, Klankermayer and Leitner 2015).

2.2. CO_2 sources

The CO_2 necessary for CCU technologies can be acquired from diverse sources; these are, however, associated with varying costs as well as effects on the environment (for details see Chapters 3, 4 and 5). In some chemical processes, for example, fermentation or ammonia production, extremely pure CO_2 is created as a by-product. This CO_2 can be isolated with the aid of commercially established recovery technologies and made available in an extremely high degree of purity for utilisation. But CO_2 can also be filtered out of flue gases, either from power plants or other industrial point sources, and made available for further utilisation (or storage) with the aid of technologies for CO_2 capture.

The CO_2 concentration at the respective 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 in which the capture is to be carried out, the less technical effort is required for capture. CO_2 can potentially be extracted from numerous industrial sources, including industrial chimneys and large coal-fired power plants. The procedures which exist today already make it possible to provide large quantities of CO_2 in 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.

A further source of CO_2 is the atmosphere. Another approach, which is, however, not currently commercially viable, plans to use chemical-technical procedures to filter previously emitted CO_2 back out of the atmosphere (Direct Air Capture). These technologies, however, still require large amounts of energy and are, for this reason, expensive, but they are currently being tested on a pilot scale by some companies such as Climeworks AG[1] in Switzerland and Carbon Engineering[2] in Canada. For widespread implementation, however, long-term technological advances are necessary, for example, in the form of new materials which could be deployed as absorbers (Krämer et al. 2015) – required to operate such technology economically. They will, however, remain inferior in comparison to CO_2 point sources of high concentration. Furthermore, renewable energies should be used[3] to provide a contribution to a positive carbon footprint by means of capture from the air.

With regard to both CO_2 capture from the air and CO_2 capture from industrial sources, it should be clear that the employed technologies, depending on the materials used, can also have undesirable effects on the environment; in some cases such effects are still insufficiently understood (for details see Chapters 3 and 4).

2.3. Possibilities and limits

With CCU technology, it is only possible to **use a limited amount of CO_2** industrially. Optimistic estimates assume that approximately 250 Mt (approx. 0.6% of the anthropogenic CO_2 emissions in the year 2014) of chemicals, and 2 Gt (approximately 5.5% of the anthropogenic CO_2 emissions in the year 2014) can be used for fuels (Ausfelder and Bazzanella 2008). Compared with anthropogenic emissions of approximately 37 Gt. of CO_2 in the year 2014 (VCI and DECHEMA 2009, Le Quéré et al. 2014), the proportion that could potentially be used is relatively small at around 6%.

There are still no reliable estimates for the total actual implementable saving of CO_2 emissions, due to the fact that the usable emissions described do not correspond with the actual saved emissions: the emission 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 this. It is even possible that an increase in emissions will occur (please also refer to Chapter 4).

[1] http://www.climeworks.com/, http://www.zol.ch/bezirk-hinwil/hinwil/In-Hinwil-entsteht-erste-Anlage-zur-CO2Filterung-aus-der-Luft/story/14037273.

[2] http://carbonengineering.com/, http://www.heise.de/newsticker/meldung/Pilotanlage-zur-CO2-Abscheidung-aus-der-Luft-in-Kanada-2847918.html.

[3] Under certain circumstances, the usage of natural gas can also be advantageous.

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 lifetime. The expected variation of the duration of storage can be days, weeks (fuels), or years (plastics), and even centuries for building materials similar to cement or insulating materials (Styring et al. 2011, von der Assen et al. 2013). In the case of direct utilisation, for example for cooling or for carbonated beverages, the CO_2 is emitted again immediately upon usage.[4] Consequently, the CO_2, in most cases, is released into the atmosphere at, maximum, mid-term delay, although it is of course theoretically possible that it could be exploited again from product fumes following incineration processes (e.g. waste incineration).

How much crude oil or other **fossil resources** could be saved in total with CCU technology, on the basis of CO_2 as a source of carbon cannot, however, be stated from the perspective of our current knowledge. It is necessary to consider all applications in their own right and to individually calculate the potential for savings of each industrial method. For the overall evaluation, optimisation of processes due to the implementation of CCU technology also plays a role that can lead to indirect emission savings. Since the majority of the relevant technologies are still in early developmental stages, such assumptions are, as yet, difficult to foresee.

By no means least, **the effects of political constraints on location** influence the institutional promotion of the development of CCU technologies. It can be assumed that a highly industrialised country with a strong chemical industry, such as Germany, not only has an economic and ecological interest in the exploitation of alternative carbon sources, but also a political one, from the perspective of dependence on the corresponding imports and the reduction of this dependency.

Detailed evaluations of the aspects of CCU technology mentioned here are to be found in the related chapters of this study. Furthermore, the final chapter of this report contains a summary of recommendations for decision makers and disseminators from the fields of politics, economy and society.

2.4. Examples for application for CCU technology

2.4.1. Direct utilisation of CO_2

So-called direct utilisation of carbon dioxide, i.e. usage without chemical transformation in solid or liquid form – is already common in various products. These include:

- carbonic acid in drinks,
- dry ice for cooling of foods,
- in fire extinguishers,
- fertiliser in greenhouses,
- in packaging or for improvement of the shelf life of foods.

As an industrial gas, CO_2 is finding further limited use in special processes. Usage of CO_2 as a coolant in car air-conditioning systems could also be more widespread in the future (Daimler 2016, UBA 2016). One direct industrial implementation worthy of mention is the usage of CO_2 in several countries for enhanced oil/gas recovery (EOR/EGR) (for details see Chapter 5). Here, carbon dioxide is pressed into the corresponding geological reservoirs for tertiary exploitation in order to win more crude oil or natural gas from the respective sources (US DOE n.d.).

[4] The processes named here as examples are already established in usage and are frequently not taken into consideration when assessing new CCU technologies.

2.4.2. Utilisation as a material after chemical transformation

Furthermore, CO_2 can serve as a raw material in chemical transformation for the production of carbon compounds of energetically higher value or of lower value. This so-called utilisation as material as a component of materials, of chemicals and of minerals is already common in:

- pharmaceutical products
- solvents
- fertilizers (e.g. urea)

In addition, it is technically feasible to use CO_2 in the manufacture of:

- plastics and foams,
- paint and coatings,
- building materials similar to cement (so-called minerals).

These innovative procedures are generally processes which are currently still in development or which became feasible due to breakthroughs in catalysis research within the scope of research on CCU technology. That decisive breakthroughs have been achieved in the past years is not least due to private and public investment in various industrialised states in which CCU research programmes have been implemented.

An overview of these sponsorship programmes, and of innovative products on the basis of CO_2 that are already globally available can be found in Chapter 5.

2.4.3. Utilisation in energy sources or as energy storage following chemical transformation

Generally, it is also feasible to use carbon dioxide as a raw material in order to manufacture energy sources. It is possible, for example, to produce the following energy sources from CO_2 by means of diverse processes:

- liquid fuels such as methanol (e.g. CRI in Iceland), diesel (e.g. Sunfire in Dresden)
- synthetic gas (e.g. Audi in Werlte)

Such energy sources can directly serve the mobility sector or could find future use as energy storage, in order to use peaks in the generation of renewable energies.[5]

A comprehensive overview of the technological possibilities of CCU can be found, for example, in the following publications:

- Verwertung und Speicherung von CO_2 (Ausfelder and Bazzanella 2008)
- Carbon dioxide as chemical feedstock (Aresta 2010)
- Carbon Capture and Utilisation in the green economy (Styring et al. 2011)

[5] More information on these concepts is available, for example, in the following literature: (Varone and Ferrari 2015), (Sternberg and Bardow 2015).

CCU as an example of technical solutions in the Anthropocene

The term "Anthropocene" originates from Earth system science and was originally coined by scientists of the International Geosphere-Biosphere Programmes (IGBP) around Will Steffen, Eugene F. Stoermer and Paul Crutzen (Crutzen 2002, Steffen et al. 2007). The term is based on the observation of grave changes in the indicators which serve to fully describe the Earth-ecological system (Steffen, Grinevald, et al. 2011, Steffen et al. 2015). All these changes, according to the conclusions of the IGBP, can be directly or indirectly attributed to the effects of human intervention on the world-ecological system. On this basis the realisation is founded that the Earth is now in a new geological era: an age in which humanity in its collective is the dominant force in the Earth system. The Earth is, therefore, no longer in the Holocene, but in the age of the human – the Anthropocene (from the Greek anthropos = the human/man). Since the time of first being introduced, the term "Anthropocene" has been discussed over the past decade in circles concerned with topics reaching far beyond Earth system science and has recently been officially confirmed by the International Commission on Stratigraphy as a new geological era (Carrington 2016, Subcommission on Quaternary Stratigraphy 2016).

On the basis of the observations of the IGBP on the grave and anthropogenic changes in the Earth system, a further concept of so-called planetary boundaries has since come into being (Rockstrom et al. 2009). In this concept, the notion is expressed that, within the Earth-systemic indicators, specific guiding rails can be identified within which, from the perspective of Earth systemics, a safe operating space for humanity exists.[6] These guiding rails are not to be considered in isolation from each other, but rather represent cross-linked aspects which are mutually dependent. This concept which, in particular, reflects the ecological maximum capacity of planet Earth, was quickly supplemented by the social guiding rails of global humanity (Raworth 2012).

[6] These include, for example, an intact ozone layer, the global climate, the extent of biodiversity, chemical pollution and an intact phosphorus cycle.

The discussions on the Anthropocene and later the planetary boundaries have served to heavily influence the corresponding discourse on the new roles and the responsibility of humanity for the general state of the planet, (Steffen, Persson, et al. 2011). In particular, they have led to the creation of new and more tangible global terms of reference within which endeavours for sustainability can be located (Töpfer 2013). This new understanding of the globally effective role of humanity, and in particular the mutual contingency of the various challenges, was also expressed in the passing of the 2015 Sustainable Development Goals of the United Nations, which bring ecological, social and economic goals into a joint context (UN Sustainable Development Knowledge Platform 2016).

In the face of these challenges, technological suggestions for achieving sustainability have been confronted with the necessity to think and develop these in more complex contexts. It has never been more important to understand technological development within a multi-dimensional target corridor, finding holistic suggestions for solutions in order to approach and develop ecological, social, and economic challenges – ideally in the same way. With this in mind, the development of CCU technology is also confronted with the challenge of making a holistic contribution in the respect of sustainability, rather than simply considering isolated sub-aspects. In concrete terms, this refers to, in the case of CCU, for example, mitigation of global warming and development of sustainable resource bases. Here, it is also necessary to develop strategies which support global abandonment of utilisation of fossil fuels (decarbonisation), without, for example, causing detrimental effects on biodiversity.[7]

In general, CCU technology is still in the early stages of development; therefore, it has potential, within the scope of its further development, to point out how it is possible to make technological contributions – within the context of the current interlinked global challenges – that could potentially bring several of these goals together in a practicable fashion. In this way, concepts for CO_2 utilisation could create examples of how sustainable technological development might become feasible in ways that do justice to the new global and systemic responsibility of humanity in the Anthropocene era.

[7] These aspects are subject to controversial discussion and criticism, for example, within the context of biofuels and bio-based materials.

"Can CO_2 be recycled? A dialogue on Carbon Capture and Utilization (CCU)" on June 5th, 2014, at the IASS Potsdam. Here: Introduction in CO_2 utilisation by Prof. Dr. André Bardow, Chair for Technical Thermodynamics, RWTH Aachen. © IASS/Christian Kruppa

"Can CO_2 be recycled? A dialogue on Carbon Capture and Utilization (CCU)" on June 5th, 2014, at the IASS Potsdam. Chair: Christoph Drösser, ZEIT. © IASS/Christian Kruppa

3. Ecological aspects of CCU technology: Effects of CO_2 capture on the environment

3.1. Background

In order to obtain a holistic assessment of the effects of CCU technology on the environment, it is important to not only consider the environmental impacts of the actual *utilisation technologies*, but also the sources from which the CO_2 to be utilised is captured. In principle, a multitude of possible sources can be considered, ranging from natural CO_2 sources found, for example, in rocks, to large industrial point sources such as exhaust streams of coal-fired power plants, cement works, or ambient air (von der Assen et al. 2016). The respective concentrations of CO_2 at these sources are extremely varied, from 0.04% in the atmosphere to over 90% in the exhaust stream of ammonia synthesis or fermentation from biomass (in this regard see also Chapter 5.2.1).

Due to the fact that the CO_2 used in CCU technology often requires a high degree of purity (> 99.9%) (Markewitz et al. 2012), it is a requirement for most eligible sources, that the CO_2 must be captured and separated with suitable technology before any possible use. This CO_2 capture is associated with a certain degree of effort which can vary depending on the chosen source and the technology applied, and in particular depends on the concentration of CO_2 and the degree of impurity in the respective source (please also refer to Chapter 5.2.1).

With regard to the capture of CO_2 both from power plant exhaust gases (as discussed and developed in particular within the context of so-called CCS technology) or indeed from the ambient air, complex procedures are required due to the low CO_2 concentration which are associated with diverse side-effects (Dautzenberg and Bruhn 2013). There is currently one class of technology for which the most comprehensive empirical values are available and which is currently the benchmark for a large-scale capture of CO_2, for example, in gas power stations, oil refineries, and in aluminium production (Ahn et al. 2013): wet-chemical washing processes with the aid of strong alkaline solutions, in particular, so-called "amine scrubbing"[8] which has been known since the 1930s and is already successfully deployed (Rochelle 2009). In particular, this technology allows (in contrast to, for example, the so-called Oxyfuel process), to retroactively upgrade existing industrial plants with chemical washing processes such as amine scrubbing ("Retrofit"). Due to the particular importance of this technology, the impacts on the environment of amine scrubbing will be considered more closely in the following section.

[8] Wet-chemical washing processes involve diverting an exhaust stream through a so-called absorber solution. The CO_2 contained in the exhaust stream is then absorbed by the molecules of the absorber solution and separated from the remaining exhaust stream. In the case of amine scrubbing, this absorbing mixture is based on a solution of amines. "Amines" are molecules based on triple-bound nitrogen (organic derivatives of ammonia). By heating the absorber solution in a subsequent process step, the absorbed CO_2 can be separated from the amine solution again and re-diverted in high concentrations. After heating, the amine solution is then diverted back into the first process step and is available for renewed CO_2 absorption. A simple portrayal of the chemical absorption process is to be found for example under http://www.tcmda.com/en/Technology/. For further details on amine scrubbing, we refer here to the relevant references: (Rochelle 2009)

3.2. Amine scrubbing and its impacts on the environment

Generally, CO_2 capture leads to a reduction of the efficiency of a power plant, due to the increased energy requirements. In the case of amine scrubbing, this lies at approximately 11% (US DOE and NETL 2010). It is not least due to this increased energy requirement, that the capture of CO_2 can be expected to lead indirectly to increased air pollution (Horssen 2011). Furthermore, during amine scrubbing there are a few further specific environmental side-effects which can occur, in particular with regard to air quality, which should be considered and which have been under increasing scrutiny and interest of science as well as parties from industry and politics over the past years (Mertens et al. 2012).

These specific side effects occur, in particular, because during amine scrubbing a proportion of the utilised amine solutions (160 g Amine per captured tonne (t) CO_2) (Knudsen et al. 2009) is released into the ambient air of the capturing plant (Nielsen et al. 2010, Karl et al. 2014). The released amines are emitted in the gas phase as well as in the form of aerosols[9] (Khakharia et al. 2013, Mertens et al. 2014). The amount of released amines increases significantly if soot or aerosols of sulphuric acid are contained within the flue gas which is being cleaned using this method (Khakharia et al. 2013).

While these amines (usually monoethanol amine – MEA or dimethyl amine – DMA) are not generally considered hazardous in their own right, the various reaction processes which take place in the atmosphere when using them can lead to harmful side-effects. These include:

(1) formation of carcinogenic nitramines and nitrosamines,
(2) formation of secondary aerosols,
(3) formation of low-level ozone,
(4) risks due to chemical waste from the utilised amine solution.

Concerns regarding the formation of carcinogenic nitramines and nitrosamines[10] have aroused growing interest over the past years in regard to both science and government along with other representatives concerned with CCS; subsequently, intensive preoccupation with this topic has been triggered (Knudsen et al. 2009, Shao and Stangeland 2009, Nielsen et al. 2010, Veltman et al. 2010, Rohr and Knipping 2011, Mertens et al. 2012, Gentry et al. 2013). The carcinogenicity of nitrosamines is well researched, although, however, the exact health impacts of nitramines have not yet been defined with sufficient accuracy. The Norwegian government has, therefore, decreed for the test plant in Mongstad, that the total amount of nitrosamines and nitramines to be released into the air shall not exceed 0.3 ng/m³; for nitramines and nitrosamines released into the water supply, the threshold lies at 4 ng/l (Norwegian Climate and Pollution Agency 2010).

While Veltman et al. estimated in 2010 that the pollution of drinking water with poisonous substances due to amine scrubbing in the vicinity of a CO_2 capturing plant could rise to around 10 times the usual concentration (Veltman et al. 2010), the concentration of nitramines and nitrosamines to be expected in the air (0,6–10 pg/m³), in the soil and in the drinking water (0,04–0,25 ng/L) in the vicinity of an amine-based CO_2 capturing plant, would lie, according to the most recent calculations, below the thresholds considered as a concern for health by the Norwegian environmental authorities (Karl et al. 2014).

[9] Aerosols are solid or liquid suspended particles in a gas. They can be of natural origin, for example, pollen or mineral dust, or they can be the residue from incineration such as soot. Secondary aerosols are particles which are formed in the atmosphere through the reactions of condensation nuclei.

[10] Nitramines are a particular sub-category of Amines, so-called nitrified amines, which include an NO_2 group. This is the same for the nitrosamines which include a so-called nitroso group (NO).

At the same time, however, the calculations show that interference effects would occur that would lead to higher concentrations, if further CO_2 capture plants of a comparable scale were operated within a distance of less than 100–200 km. Here, it must be considered that the calculations were carried out specifically for the CO_2-capturing plant in Mongstad in Norway, where the ambient air only shows a very low degree of pollution. The results regarding formation of various degradation products of amines, however, depend, in particular, on the meteorological conditions at the location of the respective CO_2-capturing plant. In particular, in heavily industrialised regions with a high density of possible CO_2 sources, such as, for example, the Ruhr area (enCO$_2$re 2016) or the east coast of China (Boren 2016), it can be considered that the introduction of amine-based CO_2 capture over an extensive area would lead to considerably higher concentrations of nitramines and nitrosamines than were calculated for the environment of the plant in Mongstad. The exact quantification would be the subject matter of detailed chemical-atmospheric model simulations similar to the ones that were developed and used for the region around Mongstad.

Karl. et al. draw attention to, in addition, the fact that the current health regulations for the permitted concentration of nitrosamines, at 0.1 ppt (e.g. in Norway) are lower than measurable with the currently available measurement methods (Karl et al. 2014). Prior to the building of a plant, detailed calculations for the specific situation of the plant in question would be necessary in order to ensure that these thresholds would not be exceeded in the direct environment around the planned CO_2-capturing plant. Methods and mechanisms for such simulations were developed by Karl et al. within the context of their current work and are available to the general public (Karl et al. 2014).

It can, in general, be said that the chemical reactions of amines in the atmosphere and in CO_2 absorbers are currently still being intensively investigated (Fine et al. 2014). Due to concerns regarding the effects of amine emissions, efforts have recently been made to develop procedures which can destroy amines or filter them out of the flue gas of a CO_2-capturing plant, for example with the aid of UV light and water (Shah et al. 2013, Dai and Mitch 2015).

Current research results prove that increased formation of secondary aerosols can be expected as a consequence of increased amine emissions from CO_2-capture plants (Borduas et al. 2013, Tang et al. 2013). Aerosols are liquid or solid suspended sediment and particles that are regarded as air pollution. These can have harmful effects on human health and influence the formation of clouds and the climate as condensation nuclei (Finlayson-Pitts and Pitts 1997). In particular, regions which already suffer from increased air pollution as a result of aerosols could view this aspect as particularly problematic. Very recent calculations have estimated the possible health-related costs as a result of particle formation through the release of ammonia from absorber solutions of amine washing plants at around 31–68 USD per captured tonne of CO_2 – if no additional ammonia filters were installed at the plants (Heo et al. 2015).

The amines to be utilised for this purpose belong to the class of so-called volatile organic compounds (VOCs) which evaporate easily and, if nitrogen oxides are also involved (NO_x), can be responsible for the formation of low-level ozone [11](Atkinson 2000). Particularly in regions with increased NO_x loads, such as the Ruhr area or other regions with a high density of power plants and industrial plants, it can be assumed that amine-based CO_2 capture will lead to the increased formation of low-level ozone, which

[11] Low-level ozone is also known as photochemical smog and is considered an air pollutant, due to the fact that it acts as an irritant gas on plants and humans.

is already a problem in many cities and regions in the form of so-called photochemical smog, affecting the air quality and related to risks for human health (in particular for the respiratory tract); problems for plant growth have also been attributed to this factor (McKee 1993, Finlayson-Pitts and Pitts 1997).

Besides the side effects due to atmospheric degradation of amines, another factor is that the utilised amine solutions are only recyclable under certain conditions and would have to be disposed in the end as chemical waste, which is, of course, associated with harmful effects for the environment and for health. According to current estimates, per 1 million captured tonnes of CO_2 around 3,500–4,000 t amine waste would result which, with technological improvements, could possibly be reduced to around 1 kg of waste per 1 t of captured CO_2 (Dautzenberg and Bruhn 2013). The consequences of the disposal of this amine waste, as regards the formation of CO_2, H_2O (water steam) and possibly also the highly climate-forcing greenhouse gas N_2O (nitrous oxide) are, however, not clarified at the moment and require quantification soon. In the face of such possible undesired side effects, there are new concepts being developed for more efficient recapturing and repeated use of the utilised amine solutions (Reynolds et al. 2012). Furthermore, intensive research is ongoing for alternatives to amine scrubbing, for example in the form of adsorption or membranes.

3.3. Conclusion

The efforts for capturing CO_2 and, in that regard, also the possible impacts on the environment, are closely related to the concentration of the respective CO_2 sources. The example of amine scrubbing reveals that the possible impacts on the environment can be more complex than simply the consequences for the climate as regards the effects of CO_2 emissions, for example through increased or reduced energy demand. In addition, within the scope of Life Cycle Assessment (LCA) (for details see also Chapter 4.), a more exact quantitative analysis of the possible formation of health-endangering air pollutants is required. For many of these noxious substances (e.g. nitramines), there are no studies available which provide a sufficiently precise assessment of the health hazards they pose.

In addition, it remains to be determined whether amine scrubbing can be classified, according to current knowledge, as without cause for concern in relation to health and compatibility with the environment. This refers, however – and this is of central importance – in particular to large-scale use, such as that intended in carbon capture and storage. Amine scrubbing is particularly seen as necessary when it comes to capturing large quantities of CO_2 from large emitters. In the case of small plants with smaller captured amounts, in contrast, the effects on the environment to be expected are accordingly smaller. Quantifying the effects on the environment of various scales of possible deployment of amine scrubbing remains an essential task for current research on this topic.

As will be shown in the following chapter, the total amounts of CO_2 which have to be captured for CCU applications are considerably smaller than the quantities being discussed for CCS. The corresponding comments there make clear that it is, in particular, feasible to cover short- to mid-term needs for CO_2 in CCU applications with higher concentrated CO_2 sources for which the utilisation of amine scrubbing is not necessary. The demand for CO_2 for CCU can also be covered with the aid of carbon-capture technologies which do not involve the risks of amine scrubbing described here.

- In the case of use on a larger scale, for example, the capture of the entire CO_2 emission of large fossil power stations, such as is planned for CSS, then amine scrubbing cannot, at present, be classified as being of no cause for concern.

- For the capture of comparably smaller quantities of CO_2, such as will be necessary in the foreseeable future for CCU applications, there are currently no concerns regarding significant risks to the environmental or health.

- In particular, the deployment of wet chemical absorption processes can be avoided by utilising higher concentrations of CO_2 sources for supply with CO_2.

- Future developments in the field of amine-based procedures for CO_2 capture shall serve facilitate the avoidance of the release of degradation products or components of utilised amines into the environment, particularly the atmosphere. This could, for example, be realised through immobilisation of the utilised amines or the integration of suitable filtering equipment.

A COMPARISON WITH THE NATURAL USE OF CO_2 IN FORESTS

In order to be able to better categorise possible contributions to containment of climate change, it is interesting to compare CCU with the natural utilisation of CO_2 as a raw material in forests. Relevant literature contains various estimates for possible long-term CO_2 consumption through CCU technology. In the case of chemicals and materials, a potential consumption of around 200 Mt of CO_2 p. a. is estimated in most cases, while the production of fuel could utilise around 2 Gt of CO_2 in the long term (see Section 5.). For long-term and large-scale CO_2 reductions by means of CCU technology, there are currently no reliable approximations.

As a comparison, the growth of terrestrial ecological systems eliminates approximately 3 Gt of carbon from the atmosphere annually, which corresponds to around 11 Gt of CO_2 (Canadell and Raupach 2008). Determining the contribution of forests and forestry management measures for the reduction of climate change is complex; current estimates lie in the region of 30 % of the global CO_2 emissions from incinerated fossil fuels and net deforestation (Canadell and Raupach 2008). As with CCU, it is also difficult in the case of forestry management measures to determine the durability of the storage or the amounts of carbon stored in forests, due to the fact that the inventory is subject to extreme variation (Canadell and Raupach 2008).

While activities in the field of reforesting is often associated with conflicts in land usage and socio-cultural aspects, a reduction of deforestation measures is seen as a cost-effective and, simultaneously, a meaningful intervention for reducing greenhouse gases (Canadell and Raupach 2008). As regards the determination of the efficiency and the potential of these measures, however, other complex bio-physical effects must be taken into consideration – for example the possible fertilising effect of atmospheric CO_2 on the growth of trees or the potential reflection of sunlight from forests. The comprehensive potential for the storage of carbon in forests depends, therefore, on how climate protection can be reconciled with other aspects and risks (Canadell and Raupach 2008).

Even if there are no reliable estimates for large-scale reduction in emissions through CCU technology, which also include possible substitution and efficiency effects, the volume potential through preservation of forests and possible reforestation measures, at around 11 Gt of CO_2, seems far greater than the potentially used amounts in CCU applications. Just as is the case for possible future developments of CCU technology, a detailed consideration of potential ecological, economic and societal effects, as well as a systemic approach, are necessary for natural CO_2 utilisation methods if the best possible sustainable combinations of the available options for action are to be identified.

“Can CO_2 be reycled? A dialogue on Carbon Capture and Utilisation (CCU)technologies” on June 5th, 2014, at IASS in Potsdam. Here: Short overview of current research projects by Dr. Alexis Bazzanella, Head of Research and Project Coordination, DECHEMA. © IASS/Christian Kruppa

“CO2 recycling - option for politics and society? A dialogue on Carbon Capture and Utilisation (CCU) technologies” on November 9th, 2015, at IASS in Potsdam. Here: Dr. Hans-Jörn Weddige, ThyssenKrupp AG. © IASS/René Arnold

4. Life Cycle Assessment of CCU

Ana Maria Lorente Lafuente

The work package LCA in the project CO_2ntext was, as described at the beginning (see Chapter 1.1.), implemented at the Chair for Technical Thermodynamics (LTT) of RWTH Aachen University. The results processed within the context of this work package are already the subject matter of various publications (von der Assen, Lorente Lafuente, et al. 2015, Pan et al. 2016).

The following section, therefore, discusses in first line the necessity and the fundamental approach of LCA methodology, as well as its possibilities and limitations in the assessment of the effects on the environment of CCU technology. For further detailed results of the work of the project on LCA for CCU technology, separate scientific professional publications are at the planning stage (Lorente Lafuente and Bardow, in preparation)[12].

4.1. Background

Although the protection of the environment is not the only driver for motivation of economic parties in the CCU field, it is often environmental questions which are brought up in the public debate on CCU technology. Interestingly, these environmentally related arguments not only serve to provide support for CCU technology but also to provide points of criticism on them. Part of the criticism directed at CCU lies in its common points with CCS technologies in the first process steps of CO_2 capture (please also refer to Chapter 6.3.3. and 8.). In some countries, CCS is perceived as being unsafe due to possible "effects on the environment and health" due to "the hazard of leaks while the plant is in operation", "the transport of CO_2 possibly not being safe" (Wallquist et al. 2010, European Commission and TNS 2011, Bruhn et al. 2016).

As already described, CCU technology has the potential to reduce detrimental anthropogenic effects on the environment in various ways: development of more efficient production processes, storage (at least temporary) of CO_2 emissions, replacement of fossil resources, or storage of energy (please also refer to Chapter 2). Positive effects are not, however, guaranteed for the environment; rather these are dependent on the concrete processes utilised – particularly because CO_2 capture and CO_2 activation demand energy from chemical reactions.

In the current phase of technological development, in which chemical reactions are still being investigated, partly on laboratory scale and in a few pilot plants, the desired environmental potential will hopefully be confirmed by means of a thorough and transparent analysis. Such analysis requires critical observation from all sides as regards possible environmental effects throughout the entire life cycle of a product.

[12] This publication will be available on the website of the LTT at RWTH Aachen (https://www.ltt.rwth-aachen.de/cms/LTT/Forschung/-ivnp/Publikationen/).

4.2. The life cycle of a CCU product

The greatest challenge in the development of CCU technology lies in the chemical transformation of the inert CO_2 molecule. To activate CO_2, energy is generally necessary, although the production of which results in CO_2 emissions. Such new CO_2 emissions can, depending on application, be even higher than the possible savings effect. In order to make a concrete statement on the total balance of any CCU technology, the total life cycle of a CCU product must be considered.

Figure 3 shows a simplified portrayal of the life cycle phases of a CCU product: The CO_2 is captured at the source for reaction in a chemical procedure with basis materials, in order to subsequently create another chemical compound. The result of this process, a so-called CCU interim product (please also refer to textbox on page 25.), can be transformed in subsequent reactions to create other chemicals, which are then brought onto the market (as a further CCU interim product), or delivered to the manufacturer of a CCU end product. This CCU end product fulfils a function during its lifetime and will, in most cases, be disposed of at the end of its usage. From the perspective of a chemical company which manufactures a CCU interim product[13], CO_2 capture and CO_2 transport are, in most cases, upstream processes which must occur in order to have CO_2 available as a raw material. For this reason, the effects on the environment of the capture and the transport can be analysed together in order to identify and select the most environmentally friendly possibility for CO_2 supply.

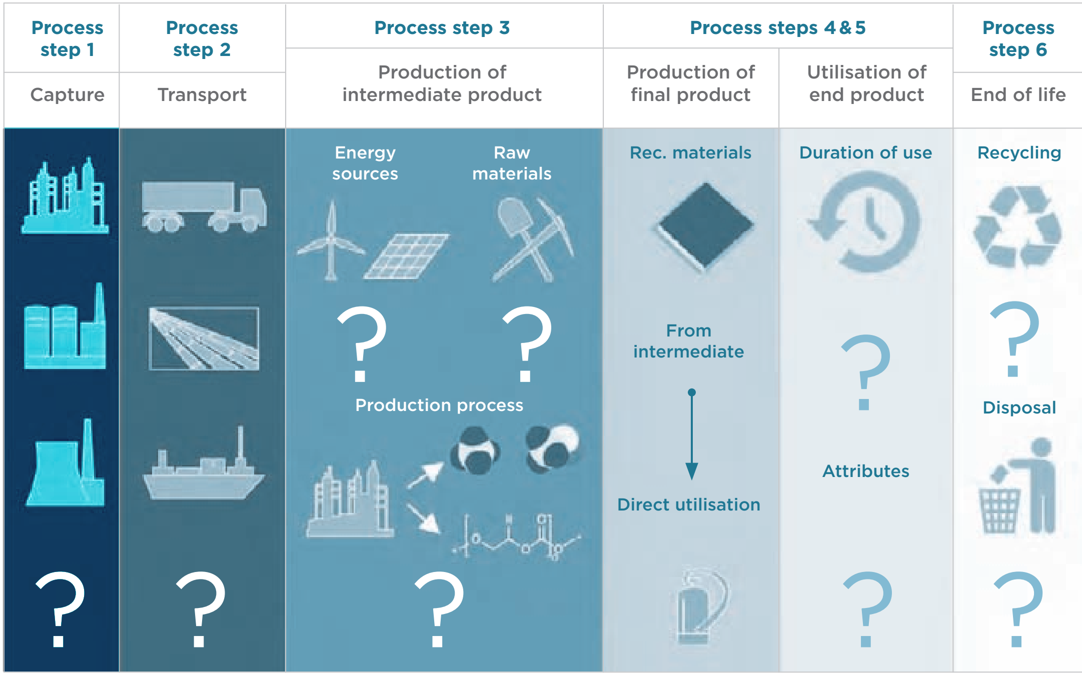


Figure 3: Life cycle of a potential CCU product

Source: Lorente Lafuente & Bardow

[13] One exceptional case in this regard is that of coupled chemical processes which take place in diverse plants of the same company.

CCU PRODUCTS: A MULTITUDE OF INTERMEDIATE AND FINAL PRODUCTS

CCU technology is extraordinarily varied in its possible areas of application and can serve extremely diverse fields. CCU products can also be intermediate or end products and, in this regard, can be relevant to business customers as well as final customers (please also refer to chapter 7).

If CO_2 is used directly without further transformation, it can take on the various states of aggregate: gaseous, for example, in the form of welding gas; liquid, for example, in fire extinguishers; or solid, for example, in the form of dry ice. In this case, CO_2 is an interim and an end product alike.

Possible intermediate products or raw materials are, for example, chemicals such as formic acid, formaldehyde, methane or methanol or specific polymer blocks such as polyols.

Potential end products are subsequently produced on the basis of such CO_2-based interim products and can, for example, be cushions or mattresses, hard plastics for housing elements for everyday objects, or building materials for houses or streets.

Some CO_2-based materials which, like methanol or methane, can be used for energy storage, can also be considered interim or end products.

4.3. The necessity of Life Cycle Assessment (LCA) for the assessment of CCU

Although CO_2 utilisation often seems sensible on an intuitive level, a quantitative and scientifically founded analysis is necessary in order to evaluate possible effects on the environment as holistically as possible. The consideration introduced here, as regards the entire process chain, is the key characteristic of the so-called Life Cycle Assessment (LCA) (European Commission 2003). According to the existing ISO standards (ISO 2006c), a LCA must be implemented in four steps: (1) Determination of the goal and the scope of the investigation, (2) Life cycle inventory (LCI), (3) Impact assessment, and (4) Evaluation. A holistic consideration structured according to this schema over the entire life cycle of a product ensures that its effects on the environment are not simply moved along the life cycle to another stage of the life cycle. The results also show whether possible environmental problems have been transferred to another category of effects (e.g. reduction of CO_2 emissions accompanied by an increase of health hazards). Consequently, the life cycle assessment is the basis on which it is reliably possible to evaluate whether, and in which way, a new process or technology is really advantageous for the environment.

4.4. Which environmental aspects of CCU technology can be evaluated with life cycle assessment (LCA)?

For the environmental evaluation, first of all, suggestions were made in the direction of CO_2-aligned ad hoc[14] indicators (Anastas 1998, von der Assen et al. 2013), for instance, the amount of CO_2 deployed per product or the duration of storage. These ad hoc indicators were intended to serve the purpose of quantification of possible advantages of CCU technology, already during the development phase; however, they proved themselves to be insufficient because, similar to the early LCAs, they could only deliver part of the information, or the information could be falsely interpreted, and/or could lead to false conclusions (von der Assen et al. 2013, von der Assen et al. 2014, von der Assen, Lorente Lafuente, et al. 2015). For example, a maximisation of the proportion of utilised CO_2 can increase the process emissions as a whole if a disproportionate amount of energy is required for this utilisation (von der Assen, Sternberg, et al. 2015). In such cases, the optimum amount of CO_2 utilisation must be determined in order to achieve the greatest benefit for the environment (von der Assen, Sternberg, et al. 2015). In contrast, very low amounts of CO_2 bonding media and CO_2 storage durations can be relevant if the process efficiency is improved. For example, some CO_2-based fuels can be produced in a way that might be more environmentally friendly than conventional manufacturing procedures, so that the net emissions end up lower, despite the extremely short duration of storage (von der Assen, Lorente Lafuente, et al. 2015).[15]

In contrast to assessment on the basis of ad hoc criteria, the result of a complete life cycle assessment, as regards the effect on the climate, is given in a single number: the total amount of CO_2 equivalents[16] which are emitted during the entire CCU process. This number makes it possible to evaluate the potential of a process as a climate-protection measure without evaluating further calculations or interpretations (Forster et al. 2007).

Further effects on the environment such as acidification, the depletion of the ozone layer, water pollution, toxicity, hazardous waste, the consumption of fossil resources etc. – all of which can be particularly relevant within the scope of the manufacture of chemicals – can also be taken into consideration in a life cycle assessment (WBCSD 2014), for example, in order to evaluate how the replacement of problematic toxicological reactants with CO_2 and H_2 affects the environment (Klankermayer and Leitner 2015).

The majority of the data necessary for the life cycle assessments of CCU products is already contained within the existing LCA databases, for example in Ecoinvent (www.ecoinvent.org); however, these databases still have to be continuously updated and supplemented. In particular, there are still some characterisation factors missing for the calculation of the effects on the environment. At the moment, for example, due to missing data and factors, it is not possible to evaluate the actual endangerment to health from nitrosamines and nitramines formed during CO_2 capture during the amine-washing process (Brekke et al. 2012) (please also refer to Chapter 3.1.).

4.5. Collection of CCU process modules for the creation of a life cycle assessment

The ISO life cycle assessment standards recommend that the product system to be investigated – in this case a complete CCU process – should be described in a system flowchart in which the process modules and their interrelations are established. This substantially eases the identification of inputs and outputs to

[14] The metrics utilised for improvement of sustainability and green chemistry are of a qualitative nature, in general.

[15] The first LCA studies which were carried out for the packaging industry could only be considered part-life cycle assessments, due to the fact that they only constituted an energy analysis for comparison of options. This was the main source of the doubt in this sector. Later, further environmental aspects such as the usage of resources, emissions and waste were taken into consideration.

[16] Carbon dioxide equivalence defines a measure for the contribution to global warming of a specific amount of greenhouse gas over a determined time period (usually 100 years) in comparison with that of CO_2. Supplementary information on the assessment of climate change is to be found, for example, in Metz, B., L. Kuijpers et al. (eds.) (2005). IPCC/TEAP Special Report Safeguarding the Ozone Layer and the Global Climate framework. Cambridge, University Press, S. 203.

be classified as elementary[17] and economic flows[18]. Figure 4 shows a schematic diagram which contains the most important modules of a CCU process with the relevant possible environmental burdens caused. These are subdivided into three categories: upstream, core, and downstream processes, depending on whether they take place before, during or after the chemical reaction.

The system flowchart also shows possible system limits during the creation of the life cycle assessment.

Not all of the illustrated processes shown here are relevant to CCU applications. The schematic illustration does, however, show, on the one hand, the fundamental approach in the creation of a life cycle assessment while, on the other, it prescribes a schema according to which CCU processes can be registered in life cycle assessments.

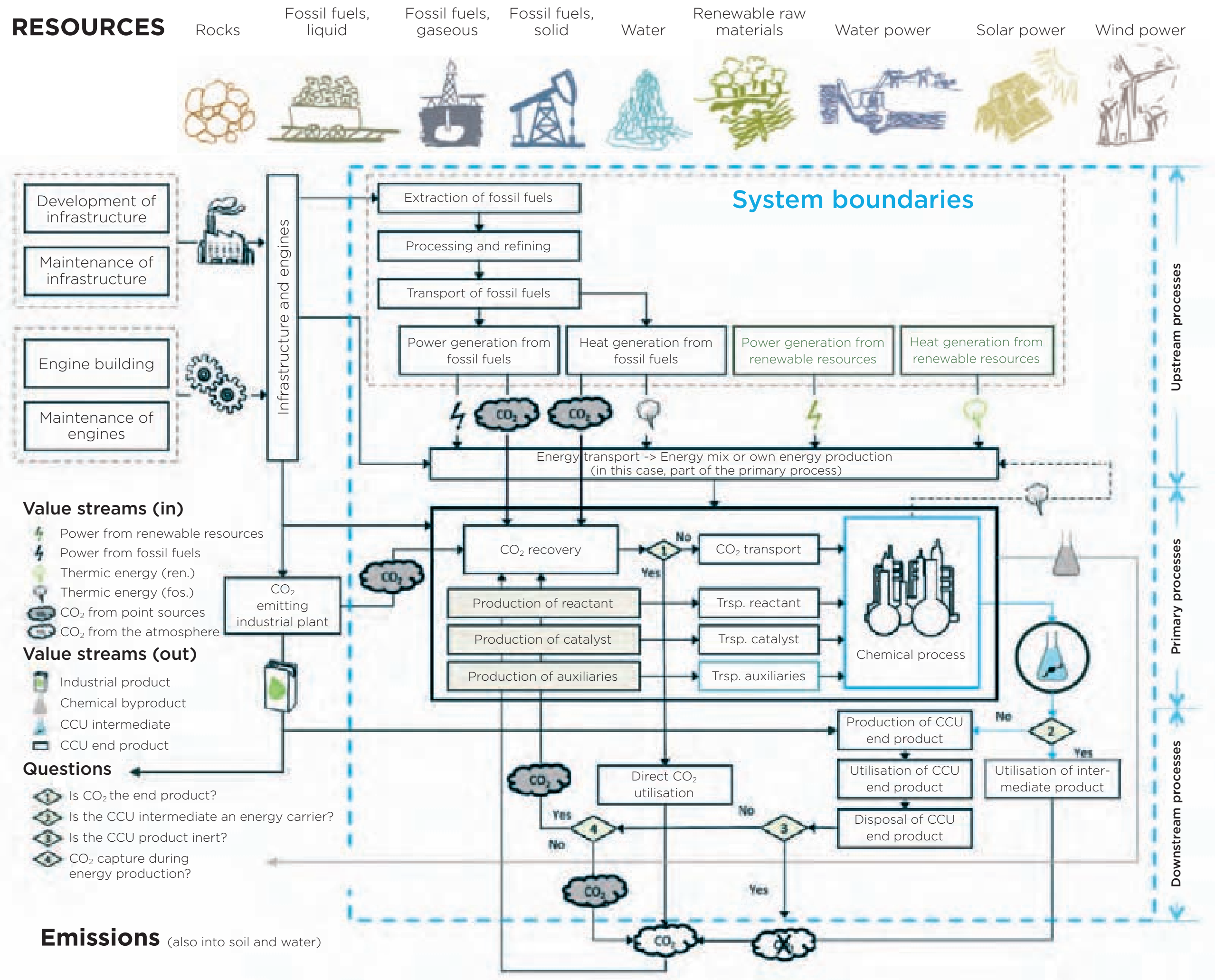


Figure 4: System flowchart for a CCU product

Source: Lorente Lafuente & Bardow

[17] An elementary flow is the material or the energy which is fed into the investigated system and was extracted from the environment by humans without previous treatment, or which leaves the investigated system and is released into the environment without subsequent treatment by humans. See also: DIN 2009.

[18] Economic flows occur between processes within the technosphere and are subject to prior and subsequent human transformation. See also: Guinee et al. 2009.

4.6. An LCA methodology for the assessment of CCU

The LCA is a method which is already around 40 years old and is continuously being developed and improved in its significance (Guinee et al. 2010). The assessment of the effects on the environment resulting from CCU technology by LCA can, therefore, serve as an example to reveal the relevance of the methodology – by the development of verifiable and comprehensive valuation standards for the effects of complex production processes on the environment. As was already addressed in the previous sections, clarification is necessary for CCU technologies with regard to their precise effects on the environment and whether they can achieve a reduction in CO_2 emissions.

4.7. The necessity of a method of consensus for public acceptance of the results

Already by the year 1999, the usage of LCA methodology was suggested as an evaluation tool for the effects of CO_2-based chemicals on the environment (Aresta and Galatola 1999). Whether and how LCA methods can be used in CCU processes has been the subject matter of various discourses for some time. Some LCA results have already been introduced and discussed at various conferences and published in scientific journals (e.g. Aresta and Galatola 1999, Aresta et al. 2002, Brentner et al. 2011, Borkowski et al. 2012, Campbell et al. 2011).

The publications have not, in all cases, managed to supply sufficient information on how the very general demands and directives of the "LCA principles and parameters and conditions" (ISO 2006a, DIN 2009) have been used in detail in order to master the complexity and unique nature of the CCU technology. Important information is often missing, such as the determination of system limits, selection of the functional unit, or the allocation processes used for allocating the inputs and outputs (von der Assen et al. 2013, von der Assen et al. 2014, von der Assen, Lorente Lafuente, et al. 2015). The absence of joint definitions and terminology for the emerging CCU technologies has impeded a unified implementation of the methodology. For example, well-founded and flawless environmental evaluations of CCU – on the basis of LCA – require, first of all, a precise definition (von der Assen et al. 2013).

At European and German federal level, the need for recognition of LCAs for CCU technology is apparent accordingly: for example, within the scope of the development programme "CO_2Plus – Stoffliche Nutzung von CO_2", ("CO_2Plus - material use of CO_2"), the Federal Ministry of Education and Research (BMBF) in Germany, in order to extend the resource basis, demands "a resilient LCA across the value chain of the processes being newly developed and/or products which the respective project has at its conclusion – e.g. according to ISO 14040 ff." (BMBF 2015).

It is also worth noting that the most recent developments in the LCA field serve to extend the traditional purely environmental focus by other dimensions such as economic or social aspects of sustainability. The so-called Life Cycle Sustainability Analysis (LCSA) is, therefore, an integrative framework for various models (Guinee et al. 2010). The assessment of CCU methods could continue to develop in this direction in the future in order to assess and quantify – in more comprehensive life cycle analyses – the innovative character of the technology and the many existing connections, in particular, as regards the important sustainability goals for resource efficiency and climate protection.

All these initiatives require the determination of joint evaluation criteria which could ultimately provide the basis for the development of product-specific demands (Product Category Rules – PCR) on declarations for CCU products (ISO 2000, ISO 2006a). Such a PCR environmental declaration for CCU should provide indications on how the life cycle assessments of CCU products are to be carried out, besides determining which information is to be provided within specific LCA reports for the general public. Such standardisation could make a transparent and comparable assessment of CCU products possible and, in so doing, provide support for increasing the acceptance of the LCA methodology and its results. In particular, the communication of the CCU environmental aspects should not only be facilitated and supported for communications between industrial representatives in this field, but also for NGOs, consumers and other peer groups (please also refer to Chapter 7.).

4.8. Current contributions to the development of an LCA method for CCU

The fundamental methodological aspects of LCA application for assessment of CCU technology have already been discussed, in particular by the Chair for Technical Thermodynamics (LTT) of the RWTH Aachen University, the location in which this work was implemented (von der Assen et al. 2013, von der Assen et al. 2014, von der Assen, Lorente Lafuente, et al. 2015). These publications describe the implementation of LCA methodology in order to avoid possible difficulties in the environmental evaluation of CCU technology, while also serving to shed light, by way of example, on the most important environmental aspects of CCU technology.

In order to chart the current state of research on LCA for CCU technology, some exemplary publications will be briefly described in the following.

An LCA method for CCU

In their article "Life-cycle assessment of carbon dioxide capture and utilization: avoiding the pitfalls" (von der Assen et al. 2013) the authors show that simple ad hoc criteria which have been used up to now by scientists to judge the effects of CCU on the environment are insufficiently resilient (see Chapter 4.4.). For this reason, the authors suggest, in agreement with other CCU experts (Aresta and Galatola 1999, Aresta et al. 2002, Peters et al. 2011), the usage of LCA methods instead. The article describes the typical application errors of LCA methodology for the assessment of CCU products on the basis of illustrated examples. One important step is that the authors identify the evaluation of the utilised CO_2 as a raw material with its own product emissions.

Additionally, one of the most significant problems with the application of LCA assessment for multifunctional processes is the selection of allocation criteria (Jung et al. 2013). The publication emphasises the effects that such a selection has when product-specific LCA results are required for CCU processes, besides offering some recommendations. In "Life-Cycle Assessment Principles for the Integrated Product and Process design of Polymers from CO_2" (von der Assen, Lampe, et al. 2015), this methodological difficulty is described using a concrete CCU example. Finally, the authors suggest a method for taking the CO_2 duration of storage into consideration within the scope of time-resolved metrics to measure the contribution to global warming. The suggested metrics make a quantification of the climatic effect of the delay of emissions and/or storage possible – a factor which varies considerably depending on which of the diverse possibilities for application of CO_2 in CCU is utilised.

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

An ecological assessment of various CO_2 sources

In the publication "Selecting CO_2 Sources for CO_2 utilization by Environmental-Merit-Order Curves" (von der Assen et al. 2016), the effects of various CO_2 sources on the entire effects on the environment of CCU processes (please also refer to Chapter 2.2.) are presented in thorough fashion. On the basis of so-called Merit-Order Curves, a method of ranking the ecologically most suitable carbon dioxide sources is introduced – as regards the categories climate protection and preservation of fossil resources. Furthermore, the publication shows several maps of Europe with so-called "CO_2-oases" and "CO_2-deserts" and describes how the CO_2 supply – depending on future CO_2 demands – would look, taking into consideration the methods of transport, the development of carbon-based industries and the electricity markets.

N. von der Assen, L. Müller, A. Steingrube, P. Voll, A. Bardow (2016). "Selecting CO_2 Sources for CO_2 utilization by Environmental-Merit-Order Curves." Environmental Science & Technology 50(3): 1093–1101.

An LCA Guideline for CCU Practice

In this publication, which is addressed mainly to chemists, "Life Cycle Assessment of CO_2 capture and utilization: a tutorial review" (von der Assen et al. 2014) a specific procedure for the implementation of an LCA for evaluation of CCU products is described. Nine particularly important aspects for life cycle assessment of CCU-based chemicals are identified and described on the basis of examples. The article emphasises the importance of the correct planning of the work with LCAs. Particularly critical is the determination of the goal and the scope of the investigation, as well as the system limits at the beginning of the analysis. Recommendations for the acquisition of data and the calculation of the effects on the environment are given and supplemented with some indications of the evaluation and the sensitivity analysis of the results.

N. von der Assen, P. Voll, M. Peters, A. Bardow (2014). „Life cycle assessment of CO_2 capture and utilization: a tutorial review." Chemical Society Reviews 43(23): 7982–7994.

LCA Standards for CCU

The book chapter "Environmental Assessment of CO_2 Capture and Utilisation" (von der Assen, Lorente Lafuente, et al. 2015) expands the content of the previously mentioned publication, to include the special focus on compliance with the regulations of the LCA-ISO standards during creation of the life cycle assessment of the CCU product in question. This is imperative when LCA users wish to communicate the results to the general public. However, the theory and many general examples are also described in this publication.

N. von der Assen, A. M. Lorente Lafuente, M. Peters, A. Bardow (2015): "Environmental Assessment of CO_2 Capture and Utilisation." In: K. Armstrong, P. Styring, E. A. Quadrelli (eds.): Carbon Dioxide Utilisation. Amsterdam. Elsevier: 45–56.

LCA as a design tool for CCU processes

Further thoughts and examples on the necessity and suitability of Life Cycle Assessment (LCA) as a CCU design tool are presented in detail in the dissertation of N. von der Assen "From Life-Cycle Assessment towards Life-Cycle design of Carbon Dioxide Capture and Utilization".

N. von der Assen (2016): "From Life-Cycle Assessment towards Life-Cycle design of Carbon Dioxide Capture and Utilization." http://publications.rwth-aachen.de/record/570980.

4.9. Is an overall ecological evaluation of CCU technology feasible?

As previously described, the current state of knowledge shows that the LCA is the only method which allows for a reliable evaluation of a product's environmental effects as attributable to the implementation of CCU technology. The methodological recommendations described in the publications continually apply, in this respect, to the assessment of a specific CCU product.

The results of an LCA can achieve a high degree of plausibility if a good – i.e. transparently created and understandable – quality of data is given with all the steps of the process, including the CO_2 source, the parameters of the chemical process, the situation in the production plant, and the energy mix. In order, however, to make a more general statement on the ecological potential of CCU as a field of technology, it is first necessary to evaluate a multitude of possible CCU interim products. Currently, the most comprehensive study of CO_2-based chemicals available (Otto et al. 2015) lists 123 examples of reactions, of which 23 are mass chemicals and 100 are fine chemicals. The scope of this steadily growing list of application examples shows the challenging nature of the task of creating a comprehensive evaluation for the entire field of technology. The task of evaluating all of the CCU-based interim chemicals can hardly be fulfilled at short notice, in particular because the CO_2-based chemical processes are generally new and, for that reason, require initially require being modelled and tried out in practice.

As a result, the answering of the superordinate question of achievable environmental goals with CCU is impeded. Due to the multitude of diverse products, the approach to this question requires a considerable shortening of the very complex LCA tasks, concentrating on the most important process elements in CCU process chemistry. Such screenings or simplified life cycle assessments make sense for obtaining a first impression of the most promising options if the most important environmental factors of the technology or a product are known. These simplified methods were therefore also recommended by environmental authorities such as the European Environment Agency (Jensen et al. 1998), in order to accelerate decision processes.

Even if a complete LCA is to follow the validation of the simplified assessment, in order to fill information gaps and improve the quality and accuracy of the results, a simplified screening method can already achieve two important goals with regard to the effects on the environment of CCU processes:

- Determine which of the options currently being analysed in the laboratory should, from an environmental perspective, be selected and further pursued for the next step: the pilot phase and industrialisation;

- Cumulative calculation of the ecological potential of CCU applications as a field of technology.

A corresponding investigation has been implemented within the context of this project and is currently in the publication process. Components of the work were already introduced at the ICCDU Conference 2016 (www.iccdu2016.org.uk).

The environmental information that can be generated using the screening method renders it possible to determine the global environmental remediation potential that might result from the introduction of the investigated CO_2-based products to the market in the future. To achieve this, however, the downstream processes ("Gate to Grave") must also be taken into consideration.

At this point lies a methodological limitation: these processes have generally been neglected up to now in CCU life cycle assessments, because CCU interim products often do not differ chemically from conventionally produced products; therefore, the introduction of CO_2-based products does not lead to any changes in the product properties. In addition, the duration of the CO_2 storage also plays a decisive role in environmentally related assessment. Not least for this reason, market effects should also be analysed in order to be able to realistically reflect and evaluate the ecological consequences of potential large-scale introduction of CCU technology. If the introduction of a CO_2-based product leads to increased demand, this will also result in additional effects on the environment. In order to model all these aspects, a so-called consequential approach is necessary during the implementation of the LCA (Kätelhön et al. 2015).

4.10. Case studies for CCU life cycle assessments

CCU technology could potentially make a positive contribution to the environment. As described, the implementation of the LCA methodology offers the possibility of founded and reliable assessment. Accordingly, there are already some publications in existence that evaluate the environmental effects of CCU applications on the basis of an LCA. These show that, under specific conditions, the implementation of CO_2 in the chemical industry can be advantageous, for example, in the manufacture of polyols (von der Assen and Bardow 2014, von der Assen, Sternberg et al. 2015). Also very promising is the CO_2sequestration as minerals, particularly if the resulting product can be used in specific fields as a replacement for cement (Pan, Lorente Lafuente et al. 2016). As regards a possible utilisation within the scope of energy storage, LCAs exist for CO_2-based methane, methanol and synthesis gas (Sternberg and Bardow 2015, Sternberg and Bardow 2016), which were determined with the aid of LCA methodology. The environmental effects of synthetic hydrocarbon fuels from CO_2 are described in the same way in Sternberg and Bardow 2016.[19]

[19] Discussion of various examples is planned within the scope of a further publication (Lorente Lafuente and Bardow, in preparation), please also refer to footnote 11.

4.11. Conclusion

It cannot generally be considered as having been ascertained that CCU technologies contribute to a reduction of CO_2 emissions in the atmosphere. Possible environmental effects of potential utilisation options of CO_2 must be considered on a case-by-case basis. To this end, an LCA methodology that can observe the entire life cycle of a product is the suitable method, because a product can have an effect on the environment in any and all phases of its life cycle. The LCA methodology is an extremely high performance tool, but also very complex. The holistic approach requires the analysis of comprehensive process chains as well as the interaction of input and output streams. For this reason, the creation of an LCA demands the cooperation of LCA experts and experts of the respective professional field being investigated.

During the assessment of CCU applications, the upstream processes, such as capture of carbon dioxide and manufacture of other reactants, as well as the chemical core processes, play key roles when determining the effects on the environment. For this reason, at least a consideration of "cradle to gate" is necessary if CO_2-based processes are to be evaluated as a more environmentally friendly alternative to conventional processes.

The downstream processes which do not lie within the direct responsibility of the users of the CCU technology can generally be neglected for purposes of comparison; there are, however, two cases in which they necessarily require to be taken into consideration:

- If the new CCU interim product does not have the same chemical composition as the conventional product that it substitutes, it could, as a result, cause a change in the product properties, the operating life or the disposal requirements;

- If the aim is to produce absolute rather than relative statements on a CCU product or on CCU technologies as fields of research.

In these cases, the total footprint of the product must be calculated, thus, a "cradle to grave" analysis is necessary.

In general, the creation of an LCA is an extremely time-demanding process, particularly due to the extensive amounts of data required. The complexity increases considerably if the recommendations to be made are not simply special, product-related recommendations, but rather general statements on technologies in their entirety, such as CCU technology, which can be used to manufacture a multitude of products with extremely diverse properties and areas of application – e.g. minerals, polymers, chemicals for energy storage or fuels. Detailed assessments continue to impede the early stages of development of many CCU technologies.

Several CCU routes have already been analysed on the basis of LCAs. Many of them seemed extremely promising from an environmental perspective. In some cases, however, the potential will only exist if assumptions on the exact value chain are made – e.g. with regard to the energy mix of the CO_2 source. Often, however, the advantages depend on the availability of hydrogen from renewable energies and, additionally, on the method of extraction of CO_2 as a raw material being associated with prevention of CO_2 emissions. Moreover, not all possible environmental contributions of CCU as a field of technology are yet known. In this regard, further supplements to the work with LCAs are necessary, using existing evaluations as a basis.

The directives prescribed in the two most important ISO-LCA Standards (ISO 2006b, ISO 2006c) are generally heeded. Consequently, their usage in practice often allows leeway for interpretation. In order to ensure ease of comparison of the LCA results, as regards reliable internal and external communication (please also refer to Chapter 7.), LCA practitioners must, however, enforce the same conditions for their analyses.

The lack of standards for CCU technology leads to the recommendation – at this point in time in technological development – to have an expert team determine specific rules of implementation for CCU=related life cycle assessments. As a consequence, a general concurrence of the research and industrial community involved in CCU technology would be necessary. This should lay out how the results are to be determined and presented. If this challenging task of harmonising were now to be approached, the demands of ISO 14025 (ISO 2006a) should provide the basis.

Both the CO_2 source as well as the energy source are of great importance for the environment-related assessment of CCU technology. For this reason, external factors such as the proportion of renewable energies in the electricity mix and the future development of coal-based power generation could have a great impact on the further development and implementation of CCU technology. Even if future CO_2-utilisation technologies actually obtained all of the required energy from renewable sources, an assessment using LCA methods would still be necessary. This is because these serve both the purpose of the ongoing analysis and discovery of improvement options and the assessment of many further environmental aspects – in particular, however, they serve the assessment of the efficiency of the process that will, in the end, be the decisive factor for the future design of more sustainable human actions and technical methods.

5. Economic aspects of CCU technology

The goal of the subproject "Economic Potential of CCU Technology" was the identification of economic aspects relevant to the further development of CCU. In addition, economic potential that might be associated with the development of the technological field of CO_2 utilisation should be taken into consideration. Taken together, these aspects and their potential form a building block for the overlapping, interdisciplinary considerations, as regards the societal perspectives of CCU.

In the first section, the political and economic parameters and conditions of CCU will be described. A market analysis then follows, including the consideration of current and possible future scenarios of CO_2 supply and demand. Following this, light will be cast on the economic potential; recommendations will then be derived for decision makers.

5.1. Political and economic parameters and conditions of CCU

In order to understand the profitability of CCU and not to mention the consequences of the large-scale deployment of such technology, the political framework conditions of CCU must first be taken into consideration. These include in particular state sponsorship of technological developments and the eco-political framework conditions, both of which affect the profitability of such technologies.

5.1.1. State promotion of CCU technology

Over the last few years, in many industrial countries, public sponsorship programmes have been started to encourage and support the technical development of technology for CO_2 utilisation, within the scope of financial efforts to protect resources and the national climate. In those countries which also plan CCS as a climate-protection measure, joint sponsorship funds generally exist for both technology fields. Table 1 offers an overview of some of the national CCU sponsorship programmes. From the objectives set out in the respective programmes, it becomes clear that the strategic added value of CCU, from technological, ecological, political and/or economic perspectives, is recognised in particular by industrialised "high-tech" nations. In addition, there are several – currently approx. 23 – further sponsorship sources, for example, the European Union. A comprehensive overview of these means of sponsorship in Europe can be found in the following database: http://database.scotproject.org/.

Table 1: Large international CCU sponsorship programmes

Source: IASS

Country	Name & year of start	Objective	Region	Amount available	Web page
China	National Key Research & Development Plan (2016)	Sponsorship of R&D in fields related to low CO_2 emissions in energy fields involving CCS, efficient transformation and use of CO_2. Demonstration of CO_2 capture with Oxyfuel	China	155 m CNY (~ 20 m EUR)	http://english.cas.cn/newsroom/china_research/201602/t20160217_159669.shtml
Germany	Technologies for sustainability and climate protection (2010)	Promotion of technology for the material utilisation of CO_2, chemical energy storage, and energy-efficient procedures	Germany	100 m EUR	http://chemieundco2.de/en/index.php
Germany	Carbon2Chem (2016)	Research on the use of blast furnace gases from the steel industry as a raw material for chemical production	Germany	62 m EUR	https://www.fona.de/de/carbon2chem-21137.html
Germany	CO_2plus (2016)	Promotion of material utilisation in CO_2-based polymers and basic chemicals, electrical, chemical and photocatalytic CO_2-transformation as well as efficient capture	Germany	15 m EUR	https://www.bmbf.de/foerderungen/bekanntmachung.php?B=1055
Germany	Kopernikus-Project Power-to-X (2016)	Setting up a national research platform on flexible utilisation of renewable resources with Power-to-X technologies in the main markets of transport, communication and chemistry	Germany	100 m EUR	https://www.kopernikus-projekte.de/projects/power-to-x
Germany	r+impuls (2016)	Promotion of innovative technologies for resource efficiency in commodity intensive production systems, from laboratory scale to industrial implementation	Germany	30 m EUR	http://www.r-plus-impuls.de/r2-de/index.php
France	ADEME/ ClubCO₂ (various sponsorship programmes) (2002)	Promotion of projects for CO_2 capture, storage and utilisation in research and on demonstration scale	France	unknown	http://www.captage-stockage-valorisation-co2.fr

Country	Name & year of start	Objective	Region	Amount available	Web page
United Kingdom	Cross-Government CCS R&D programme/ CO_2 utilisation projects (2011)	Technologies for alternative use of CO_2 including mineralisation and commercial products	United Kingdom	10 m GBP (~ 12 m EUR)	https://www.gov.uk/government/publications/cross-government-carbon-capture-and-storage-r-d-programme-2011-2015-list-of-projects
Canada, Alberta	CCEMC Grand Challenge (2010)	Promotion of innovations which transform CO_2 into new products.	Technologies from all over the world with potential for use in Alberta	35 m CAD (~ 24 m EUR)	http://ccemc.ca/grand-challenge/
Korea	Korea Carbon Capture and Sequestration R&D Center (2011)	Central research Centre for development of technology on CO_2 capture, storage and transformation (currently 11 projects in the chemical field and 6 in biological transformation of CO_2)	Korea	151 m USD (~ 135 m EUR)[20]	http://dh120.myelhub.com/_ENG/html/main.html
The Netherlands	Advanced Research Center Chemical Building Blocks Consortium (ARC CBBC) (2015)	Sponsorship of sustainable production methods and CO_2 utilisation at a joint research centre for various organisations	The Netherlands	11 m EUR p. a. (joint PPP Funding)	http://www.nwo.nl/en/news-and-events/news/2015/national-research-centre-for-chemical-building-blocks.html
The Netherlands	VoltaChem (2014)	Sponsorship of technological development for indirect and direct utilisation of renewable energy in the chemical industry	The Netherlands	2 m EUR	http://www.voltachem.com
Taiwan	National Energy Program (2014)/Carbon reduction and Clean Coal Focus Center	Development of technology for CO_2 capture, storage and utilisation with a view to reduction of emissions in the coal-based energy supply	Taiwan	unknown	http://www.nepii.tw/language/en/focus-centers/carbon-reduction-and-clean-coal-focus-center/
USA	Recovery Act/ Innovative concepts for beneficial reuse of CO_2 (2010)	Sponsorship of innovative technologies for the utilisation of CO_2	USA	100 m USD (~ 90 m EUR)	http://energy.gov/fe/innovative-concepts-beneficial-reuse-carbon-dioxide-0

[20] For details on this programme see (Carbon Capture Journal 2013).

Sponsorship programmes serve to simplify profitability trials on CCU technology already in the early stages while minimising the risks of the researching organisations. During sponsorship, the interplay across various technology fields should be considered. In many regions, sponsorship for CCU and CCS is combined (China, USA, UK, France). This applies, among others, to regions which, in the long term, rely on fossil fuels such as oil, coal and gas. In other regions, independent support for CCU without any affiliation with CCS is available; however, this usually occurs in combination with sponsorship and the development of renewable energies.

AN INNOVATION POLICY ASSESSMENT OF CCU

The EU Innovation Fund (IF) is currently being revised. To design such long-term innovation programmes which have an obligation to climate protection, the question is raised of whether, and to what degree, the CCU field of technology should be taken into consideration.

In a joint study with Raffaele Piria of Adelphi, commissioned by the BMUB, a climate policy analysis for CCU was carried out. Following this, innovation policy conclusions were drawn for the design of climate protection oriented innovation programmes; in this regard, so-called "No regret" options were formulated and specific advice issued on the sponsorship of further technological options.

R. Piria, H. Naims, A. M. Lorente Lafuente (2016): "Carbon Capture and Utilization (CCU) – Klimapolitische Einordnung und innovationspolitische Bewertung." Berlin: Adelphi.

Link: https://www.adelphi.de/de/publikation/carbon-capture-and-utilization-ccu-klimapolitische-einordnung-und-innovationspolitische

5.1.2. Environmental policy conditions as economic parameters for CCU

Established procedures for CO_2 utilisation, for example, in the food industry or in urea production, do not lead to positive life cycle assessment results (please also refer to Chapter 4). Only the new CCU processes, developed foremost with a view to ecological improvements, could therefore be supported in their further development through instruments of environmental policy. As previously mentioned, various environmental policy aspects are affected by CCU technologies. Potential contributions are to be found in the fields of resource security, climate protection and energy transformation (Bruhn et al. 2016). Even if the possible contribution of CCU to climate protection should not be overestimated (Olfe-Kräutlein et al. 2014), concrete climate policy instruments, such as accordingly higher CO_2-certificate prices, could still play an important role for the further development of CCU (please also refer to Chapter 8). In particular, in the follow-up to the COP-21 in Paris, a multitude of emission-reduction measures are expected to play a greater role in the implementation of the future ambitious goals. The ratification and implementation of the agreement in the form of concrete measures in Germany and Europe will presumably last until 2017. In order to allow the concrete individual measures to form a coherent overall picture, it is recommended not to regard capture and use of CO_2 as isolated measures, but rather as one option or contribution within a portfolio of multiple technological solutions.

Potentially relevant environmental policy measures and processes which will influence the further development, establishment and profitability of CCU technology are, besides the European Emission Trading (EU-ETS) system, the Fuel Quality Directive, the Renewable Energy Directive, and further measures relevant to the energy transformation (please also refer to Chapter 9). Currently, there are only weak economic incentives in place for industrial companies to reduce their CO_2 emissions. In particular, the long-term low price for CO_2 certificates in the EU-ETS (currently around 5 €/t CO_2) (EEX 2015) cannot be viewed as an effective means of motivating investment in industry. The visible possibility of a future rise in certificate prices would at least lead to some companies becoming more involved today in specific climate-protection technology.

The fundamental idea behind the ETS is to guarantee a specific degree of emission reduction by means of an amount-based control system and, at the same time, to make technological and economic flexibility possible. It can be said that the current framework leaves open how such a reduction is to be achieved – the most economical way forward should consequently assert itself in the end. Within this system, CCU could, therefore, be a potential way of achieving emission reductions – i.e. investments in CCU technologies could reduce the costs for CO_2 emissions expected by the ETS (which might be extremely high in the future).

Future recognition of CCU in the EU-ETS as a measure for reduction of emissions is currently being discussed in the research community (SCOT project 2016). In those cases in which CCU qualifies as a long-term method of storage of CO_2[21] – i.e. perfectly fits the definition of CCS – a form of recognition as a method of reducing emissions using existing processes should be feasible. In all cases in which CO_2 is only bound in the short- to mid-term, recognition of an emission reduction in the ETS should only be possible, exclusively, for the actual reduction in emissions achieved by the new CCU plant – determined, for example, on the basis of an LCA (Naims et al. 2015). The method by which such a credit should be verified, managed and accounted for in detail for each of the various plants is, however, still to be determined.

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. A rise in prices for fossil resources and/or availability of renewably produced energy, at as low cost as possible, on the other hand, could support the implementation of such technologies. Some technologies, however, work on the basis of achieved increases in efficiency, even at the current price levels of fossil raw materials.

5.2. Market analysis: CO_2 as a commodity

Although CO_2, from a global perspective, is generally an undesirable flue gas, it is already traded today as a commodity in some small special market segments. The consideration of possible CO_2 sources on the supply side and CO_2 applications on the demand side, is therefore sound in that it aids understanding of possible future combination possibilities and the relative scale considerations of CCU (Naims 2016). In the following, CCU products which already exist or which will soon be market-ready will be introduced.

5.2.1. CO_2 sources as supply side

CO_2 only works in industrial applications, in most cases, under the prerequisite that it is available in the highest possible concentration and degree of purity. In some cases, however, impure CO_2 or gaseous mixtures can also be deployed. A wide range of technology is already currently available for the capture and treatment of CO_2 from natural and industrial sources. The effort for capturing CO_2 depends, therefore, on the source chosen in each case and on the technology used and, consequently, the costs can vary (see Table 2).

If industrial CO_2 emissions are compared, the processes in which **highly pure CO_2** is emitted as a flue gas are regarded as the most economical source. Such sources are, 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 35 €/t of CO_2 (cp. Table 2). Some of these plants, therefore, already have technology for CO_2 capture installed in order to satisfy existing demand. A proportion of

[21] Permanent storage here refers to a duration of more than 1000 years, as suggested by the IPCC report; (Metz et al. 2005).

these CO_2 emissions is already in industrial usage today. In addition, biogas plants emit comparatively highly concentrated CO_2. These sources cause a total of around 300 Mt of CO_2 emissions annually.

The CO_2 point sources which contribute the greatest emissions, on the other hand, are **fossil fuel power stations**, which cause around 10 Gt of CO_2. The installation of technology for CO_2 capture is technically feasible at such sources, albeit associated with an average efficiency loss of around 10–30% of the energy created at the power plant (de Coninck and Benson 2014). CO_2 capture at power plants is, therefore, not an economical option at the moment 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 €/t of CO_2 can be achieved (cp. Table 2).

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

In addition, so-called "natural sources" can be eligible for CO_2 supply. These are, in first line, natural extraction sources of **CO_2 from rocks**[22] and other durably saved storage facilities. Due to the high concentration, the costs for extraction from these sources are often comparatively low, at around 15–20 €/t CO_2 (Aresta and Dibenedetto 2010). Such extraction is, therefore, already taking place today for economic reasons on an unknown scale.

In addition, capture of **CO_2 from the air** is currently already technically feasible; however, due to the comparatively low CO_2 concentration of around 400 ppm bzw. 0.04%, this is associated with high energy requirements and is therefore not an economic option. In future, however, scenarios in which high availability of cheap renewable energy is assumed, and capture of CO_2 from the air could thus become an interesting technological option.

5.2.2. Scenarios for CO_2 utilisation on the demand side

Already today, there is a demand for CO_2. In special applications such as, for example, carbonated drinks or food packaging, as well as many other areas of use, CO_2 can be directly deployed in liquid or gaseous form. To this end, roughly around 20 Mt CO_2 is currently in use. If the roughly 25 Mt of CO_2 used in tertiary oil/gas recovery (EOR/EGR)[23] are added to this sum, this so-called "physical" or "direct" use of CO_2 rises globally to somewhat more than 40 Mt (cp. Table 3). New direct areas of application for CO_2 are currently being developed for various areas: for example, CO_2 can be used as an interesting alternative coolant in air-conditioning systems for cars or in dry cleaning, replacing the usage of other harmful substances or valuable resources (Malvicino 2011, Madsen et al. 2014).

Furthermore, CO_2 can be used as a chemical building block for the production of other materials, chemicals and fuels.

Currently, in the chemical industry, around 180 Mt of CO_2 are used (cp. table 3). The greatest proportion of this, around 114 Mt, is used in the production of urea. The CO_2 in such cases originates mostly from ammonia synthesis, due to the fact that the industrial coupling of these processes is common.

[22] It is to be found, for example, in the pores of sediment. At the Pisgah Mountain Saddle in the US American state of Mississippi – approx. 250 Mt of CO_2 have been in storage for around 65 m years; see (IEA Greenhouse Gas R&D Programme 2005). But also mineral water manufacturers extract water and "natural carbonic acid", in part jointly, from underground sources. By way of example, this is graphically explained on the following Internet page: https://www.gerolsteiner.de/de/wasserwissen/quelle-ursprung/.

[23] Enhanced Oil or Gas Recovery (EOR/EGR) refers to procedures in which additional amounts of fossil fuels, following primary and secondary extraction, are extracted from oil and gas fields by means of injection of CO_2. The CO_2 then remains, in smaller or greater amounts, within the empty reserve; cp. (IEA 2015).

Table 2: Potential CO_2 sources

Source: Naims (2016), adapted from Wilcox (2012), US EIA (2014), Metz et al. (2005) among others

CO_2 emitting source	Global emissions (Mt CO_2/year)	CO_2 content (vol %)	Estimated capture rate (%)	Capturable emissions (Mt CO_2/year)	Benchmark Capture cost (€$_{2014}$/t CO_2)	Group of emitters
Coal to power	9,031	12–15	85	7,676	34	fossil-based power generation
Natural gas to power	2,288	3–10	85	1,944	63	fossil-based power generation
Cement production	2,000	14–33	85	1,700	68	industry large emitters
Iron & steel production	1,000	15	50	500	40	industry large emitters
Refineries	850	3–13	40	340	99	industry large emitters
Petroleum to power	765	3–8	not available	not available	not available	fossil-based power generation
Ethylene production	260	12	90	234	63	industry large emitters
Ammonia production	150	100	85	128	33	industry high purity
Bioenergy	73	3–8	90	66	26	industry high purity
Hydrogen production	54	70–90	85	46	30	industry high purity
Natural gas production	50	5–70	85	43	30	industry high purity
Waste combustion	60	20	not available	not available	not available	industry large emitters
Fermentation of biomass	18	100	100	18	10	industry high purity
Aluminium production	8	<1	85	7	75	industry large emitters

Table 3: Estimate of the global CO_2 demand

Source: Naims (2016), adapted from Aresta, Dibenedetto et al. (2013)

Product /Application in Kilotonnes (kt) p. a.	Current est. volumes		Midterm est. volumes (~ 10 years)	
	CO_2 input	Product output	CO_2 input	Product output
Direct use	**42,400**		**42,400**	
Beverage carbonation	2,900	2,900	2,900	2,900
Food packaging	8,200	8,200	8,200	8,200
Industrial gas	6,300	6,300	6,300	6,300
Oil and Gas Recovery (EOR/EGR)	25,000	7–23% of oil reserve, <5% of gas reserve	25,000	7–23% of oil reserve, <5% of gas reserve
Materials & chemicals	**167,515**		**212,400**	
Urea	114,000	155,000	132,000	180,000
Inorganic carbonates	50,000	200,000	70,000	250,000
Formaldehyde	3,500	21,000	5,000	25,000
PC (Polycarbonates)	10	4,000	1,000	5,000
Carbonates	5	200	500	2,000
Acrylates	0	2,500	1,500	3,000
Carbamates	0	5,300	1,000	6,000
Formic acid	0	600	900	1,000
PUR (Polyurethanes)	0	8,000	500	10,000
Fuels	**12,510**		**20,000**	
Methanol	8,000	50,000	10,000	60,000
DME (dimethyl ether)	3,000	11,400	> 5,000	> 20,000
TBME (tertiary butyl methyl ether)	1,500	30,000	3,000	40,000
Algae to biodiesel	10	5	2,000	1,000
Total	**222,425**		**274,800**	

From an ecological and an economic perspective, the newly emerging CCU applications are particularly interesting – these attempt to utilise CO_2 as a source of carbon for the production of other useful substances and, in so doing, replace conventional procedures, in particular fossil raw materials. These new CCU applications are currently still being tested on a laboratory, pilot, or demonstration scale, with first products already available on the markets. In the long term, however, they could lead to an annual demand of around 250 Mt of CO_2 for the manufacture of carbon-based materials (Ausfelder and Bazzanella 2008). For the manufacture of synthetic fuels, around 2 Gt CO_2 could also be used annually (Ausfelder and Bazzanella 2008) if these managed to establish themselves economically. From an ecological perspective, worthwhile areas of implementation for these kinds of fuels are, for example, ship, air, and truck traffic (UBA 2014a, Piria et al. 2016).

Without any wide-scale technological changes in energy production or industry, large amounts of CO_2-emitting point sources will still be available, from which CO_2 can be captured comparatively cheaply in the future. However, even ambitious emission-reduction scenarios, for example, by the UBA "Greenhouse Gas Neutral Germany" (UBA 2013) or by the IPCC (RCP 2.6) (Edenhofer et al. 2014) consider that "unavoidable" CO_2 emissions will remain where regions wish to, at the least, maintain their level of development and industrialisation. Taking into consideration the comparatively small proportion of amounts of CO_2 used, currently between 200 Mt and potentially around 2 Gt of CO_2, it can be concluded from a macroeconomic perspective that, also in the long term, the remaining high-purity emission sources will initially supply CCU applications, followed by those industrial sources that can provide CO_2 at the lowest possible costs of capture.

In particular, for the long-term, large-scale development of CCU, the availability of large amounts of renewable energy is, in addition, extremely conducive (please also refer to Chapter 9). A scenario which completely precludes fossil energy production shows that long-term demand for CCU purposes could also be completely covered by captured CO_2 from the largest industrial point sources of the various industries (see Figure 5)[24]. If significant emission reductions are achieved for these industries, capture from the air is an alternative to cover potential CO_2 demand.

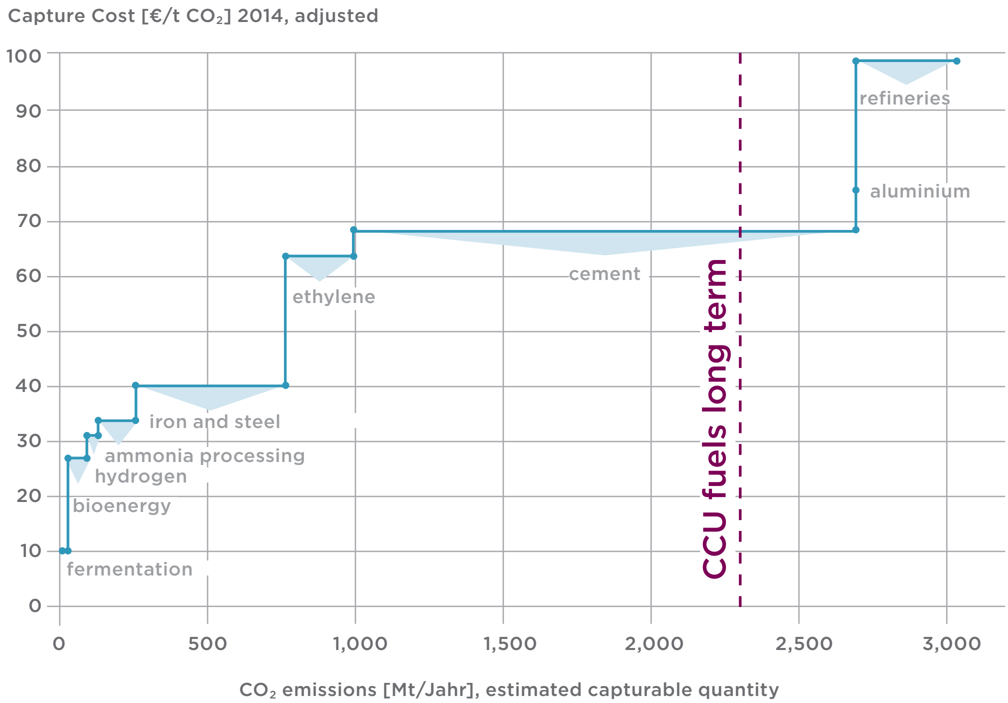


Figure 5: CO_2 supply and demand without fossil energy production

Source: Naims (2016)

In individual cases, the local availability of CO_2, in addition to other factors, also plays a decisive role. It can, for example, be assumed that decisions concerning the location for the construction of a new CCU plant will always require immediate proximity to CO_2 in sufficient quality and at the lowest possible prices. Initial considerations regarding the availability of renewable energy and CO_2 emissions reveal that numerous locations in Germany can offer both aspects (Mennicken 2015). For CCU technologies that work with hydrogen produced on the basis of renewable energy, however, in order to produce PtX process fuels or other energy sources, CO_2 is not the decisive cost factor, but rather the price of renewable energy and renewably generated hydrogen. The degree to which the availability and the costs of CO_2 influence the production process is specific to the technology used.

[24] For further scenarios and detailed representations see (Naims 2016).

Table 4: New CO_2-based products from all over the world

Source: IASS

Product	Company	Region/ country	Areas of use	Web page
Direct use				
CO_2 washing machine	Tersus Solutions	USA	Dry cleaning of textiles with CO_2 instead of water	http://www.tersussolutions.com/lco2solution/
CO_2 as a refrigerant	Daimler	Europe	Air-conditioning systems for cars with CO_2 as a refrigerant	https://www.daimler.com/dokumente/investoren/nachrichten/kapitalmarktmeldungen/daimler-ir-release-de-20151020.pdf
Materials & chemicals				
Plastics	Covestro	Germany	CO_2-based polyols for the manufacture of foam, e.g. for mattresses	http://presse.covestro.de/news.nsf/id/aazc76-premiere-fuer-neuen-rohstoff
Plastics	Econic	United Kingdom	CO_2-based polyols for the manufacture of foam, e.g. for mattresses	http://www.econic-technologies.com/catalyst-technology/carbon-dioxide-as-a-feedstock/
Plastics	Novomer	USA	CO_2-based polyols and polymers for the manufacture of various plastics, e.g. elastomers and foams	http://www.novomer.com/co2-business-overview-0
Minerals	Carbon8	United Kingdom	The treatment of industrial waste and CO_2 waste gases by processing these to minerals for use as concrete aggregate or building materials	http://www.c8s.co.uk/technology.php
Minerals	Recoval	Belgium	Treatment and processing of waste from the steel industry with CO_2 waste gases, to create minerals (granulates for road works and other building materials)	http://www.recoval.be/
Fuels				
e-Gas	Audi/Etogas	Germany	Fuels for CO_2-neutral mobility for specific Audi models	https://www.audi-mediacenter.com/de/audi-e-gas-audi-g-tron-240
e-Diesel	Sunfire/Audi	Germany	Production of synthetic fuel (diesel)	http://www.sunfire.de/de/produkt-technologie/power-core
Methanol	Carbon Recycling International	Iceland	Production of synthetic fuel (methanol)	http://carbonrecycling.is/products-1/

5.2.3. Segmentation of new CCU products

The search for new possibilities for the utilization of CO_2 which go beyond the common market-niche applications developed within the scope of the oil crises of the 1970s and the fight against climate change. These new technologies distinguish themselves through the fact that they replace other conventional technologies and resources, as well as the fact that they aim for increasing efficiency and achieving improvements related to environmental balance. Table 4 provides an overview of some of the new CO_2-based products which are offered internationally. There are many other technologies that are still in early stages of development and which require further investment on laboratory, pilot or demonstration scale.

In the field of direct CO_2 utilisation, CO_2 air-conditioning systems for cars are being discussed in particular – such systems have already been successfully tested in buses. Technical and regulatory details are currently being clarified for wide-scale use in the car market (Kilimann 2015). In addition, a CO_2-based commercial dry washing machine was introduced which, in addition to not requiring water, also offers other ecological advantages (Madsen et al. 2014).

As regards materials and chemicals, various breakthroughs have been achieved using CO_2, in particular in the field of manufacture of plastics. Globally, there are currently three companies offering technology for CO_2-based synthesis of polymers for hard or soft plastics. In Germany, in June 2016, the first demonstration plant of the Covestro company was opened in Dormagen. This will produce CO_2-based polyols for various end products such as mattresses. Moreover, in the field of mineralisation, i.e. for production of building materials, first technologies are now commercially available. Many other chemicals, materials or building materials are also currently being developed by research teams all over the world.

Furthermore, some companies are already offering the first energy carriers on the basis of CO_2 and hydrogen. While the company Carbon Recycling International, in Iceland, uses energy from renewable sources to produce fuels on the basis of CO_2 on an industrial scale, with the local advantages of geothermal energy, two smaller plants in Germany owned by the companies Audi and Sunfire are producing synthetic fuels on the basis of renewable energy from wind and solar power. Due to the low prices of fossil energy, these new technologies are, however, currently not competitive options to conventional fuels.

The UN Sustainable Development Goals (SDGs) and CCU: possible points of contact

The SDGs of the United Nations aim to introduce the global transformation towards more sustainability, although one major goal continues to be the fight against poverty. The ambitions cover a total of 17 goals which have been subdivided into respective subordinate goals. The goals are universally valid, although their implementation remains voluntary until 2030.

As regards the view to future development of CCU, numerous core and subordinate goals are consequently applicable. The SDGs can be viewed as a universal framework in which technological development should take place.

Source: UN Sustainable Development Knowledge Platform (2016)

In particular, the following core and subordinate goals seem to be compatible with the ecological and economic potential of CCU discussed in this report:

8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all

8.2 Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors

8.4 Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programmes on sustainable consumption and production, with developed countries taking the lead

9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities

9.5 Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and development spending

11. Make cities and human settlements inclusive, safe, resilient and sustainable

11.2 By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons

12. Ensure sustainable consumption and production patterns

12.2 By 2030, achieve the sustainable management and efficient use of natural resources

12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment

12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse

12.c Rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption by removing market distortions, in accordance with national circumstances, including by restructuring taxation and phasing out those harmful subsidies, where they exist, to reflect their environmental impacts, taking fully into account the specific needs and conditions of developing countries and minimizing the possible adverse impacts on their development in a manner that protects the poor and the affected communities

13. Take urgent action to combat climate change and its impacts

13.2 Integrate climate change measures into national policies, strategies and planning

Detailed Analysis of the compatibility of CCU technology with the SDGs is currently the subject of further work at the IASS.

5.3. A consideration of possible economic potentials of CCU

From an economic perspective, it is only possible to make qualitative presumptions on the effects of broad implementation of CCU technology on the basis of the knowledge discussed up to now. Currently, there is still no reliable data on the multitude of technologies (of which many are still in early stages of development) from which resilient quantitative findings can be won. The following considerations are, therefore, 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 CO_2 basis, which can be regarded as an optimistic perspective. To reduce the complexity, other, possibly less optimistic, scenarios which are included in more detailed publications (e.g. Naims 2016, Piria et al. 2016) are not discussed in the following. The overall economic potentials of CCU repeatedly correspond with the kinds of hope which often rise in connection with environmental technologies. For example, the Sustainable Development Goals (SDGs) which were passed by the UN in 2016 presume that technological progress and innovation will lead to the achievement of more sustainable economic modes and developments, and resource efficiency will play an important role in this regard (UN Sustainable Development Knowledge Platform 2016).

In the following, central economic fields such as domestic production, foreign trade, investment and financing, as well as employment and budget, will be discussed separately with regard to possible long-term implementation of CCU technology.

5.3.1. Possible effects on the domestic production

Large-scale CCU will potentially influence the industrial production in relevant regions such as Germany, Europe and North America. New procedures and plants could, in this way, lead to reductions of the **use of fossil raw materials** in the long term, particularly in the chemical industry. Furthermore, the use of numerous CCU plants could lead to a new and potentially great demand for renewable energy. In addition, the widespread implementation of CCU often requires cooperation beyond the conventional limits of industrial sectors. This results from the necessary cooperation between emitters, for example, power stations or steelworks and potential users – e.g. chemical plants. **Synergy effects** thus appear, feasible in production as does a contribution to a greater structural transformation of industry. Accordingly, it is to be hoped that the implementation of CCU could lead to **modernisation effects** for European industry which is, in part, outdated ("industrial renaissance", Wilson et al. 2015).

It is also assumed that CCU could 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; but it will depend on 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 so-called **"rebound" effects**. This is due to the fact that more raw materials overall would be used and more products and waste would be produced. These kinds of effect are often regarded and described in the context of increases in efficiency on both the producer and consumer sides (Santarius 2012, UBA 2014b).

5.3.2. Possible effects on foreign trade

Current statistics from the European Chemical Association CEFIC show that, despite the clear balance-of-trade surplus of the European chemical industry of over 43.5 bn. € 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 a foreign trade effect, the potentially reduced consumption of raw materials could, in the long term, lead to a reduction of the **dependency on import of fossil resources.**

The new types of CCU process which would lead to valuable technical know-how and several patents, could also imply a **technological advantage** in international comparison. This could have a positive effect on the export statistics if CCU technologies and products from Germany and Europe come into demand and be offered internationally.

5.3.3. Possible effects on investment and financing

One potential economic risk could be the mismanagement of public and private investments. Significant losses could occur in specific sectors if CCU processes are coupled with 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. These kinds of strategic error and lock-in effects should necessarily be avoided. Instead, as great as possible investment security should be pursued.

In addition, losses could result if significant research funding for development is deemed long-term technically or economically unenforceable or if ecologically undesired technology is advanced. For this reason, it is recommended to work 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 the basic research.

One positive effect in the area of investment financing could, furthermore, be the founding of businesses associated with CCU. In a global survey more than 50 CCU-related start-ups could already be registered of which, respectively, around 40% were market technologies for fuel production and mineralisation, while around 20% offered chemical products (Zimmermann and Kant 2016). Potential new innovations and new jobs, as well as promotion of competition and structural change, are seen as overall economic advantages of the founding of businesses (BMWi 2016).

5.3.4. Possible effects on employment and the household budgets

Innovation often leads to the hope that new jobs will be created; this expectation is often also expressed in the case of CCU (Wilson et al. 2015). The potential effects of CCU on the numbers and types of job are, however, currently not foreseeable. This will depend on how and whether the technology becomes industrially established. In consideration of the groundbreaking products portrayed in Table 4, the hope would be justified that creation of new jobs in the fields of research, development and operation of plants is probable in the future, 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 case that the level of consumption remains constant and a price difference between the CCU-based and conventional products should take place. At the moment, however, it does not seem probable that these products will be offered to consumers at a cheaper price. A higher price, in contrast, seems feasible, particularly for technologies which offer better properties for the environment and which, at the same time, are currently more expensive in production than conventional fossil raw material-based products. The decision to buy these types of product could, consequently, reduce the income of households while improving their overall environmental performance.

Rebound effects of CCU products directed at consumers are, furthermore, indirectly possible, particularly in the relevant segments of chemical products and plastics, building materials and mobility1; they are, however, not really foreseeable because no cash or time saving considered likely for the consumer. In any case, such effects would be very difficult to measure.

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

5.4. Recommendations for decision makers

No general statements can be made on the profitability of CCU technology because it is determined by the specific technology and depends on a number of factors. Large-scale deployment of CCU technology could be advantageous in the long term from an economic perspective, as long as the proper parameters and conditions are created and technological breakthroughs are achieved. It is therefore recommended, within the scope of the promotion of further development and implementation of CCU, to heed the following points:

- The further promotion of research and development on CCU technology makes sense from an economic perspective and can accelerate the accomplishment of various interesting innovations

- CCU should be imagined and implemented as an option and/or a contribution within a greater portfolio of multiple technical solutions in the sense of sustainability goals

- For CO_2 capture, numerous sources are available. As regards further promotion and development, undesirable lock-in effects should be avoided

- Some CCU-based products, in particular fuels, are currently not yet competitive in comparison to cheaper energy from fossil sources. If an ecological benefit is foreseeable, then incentives should be created to support the implementation of these technologies in specific sensible areas of utilisation, for example ship or aircraft. CCU can, in comparison to and in combination with other environmental technologies, have various positive economic effects, for example, synergy effects in production and a reduction of dependency on the import of fossil resources. The potential to benefit society as a whole should be taken into consideration and evaluated within the decision-making processes and in the further promotion of the technologies

“CO_2 recycling – option for politics and society? A dialogue on Carbon Capture and Utilisation (CCU) technologies”. November 9th, 2015, IASS Potsdam. © IASS/René Arnold

6. Perception and communication perspectives of CCU technology

Advancements in technical research are the decisive factor for the further development and industrial implementation of CCU technology. The necessity to investigate communication aspects during the early stages of technical maturity is less evident. The fact that early questioning of media reception and public acceptance should be considered in order to make successful introduction of technical innovations possible (Wüstenhagen, Wolsink and Bürer 2007) is exemplified by the acceptance problems of technological innovations such as nanotechnology, genetic engineering or CCS[26] in Germany and other European countries (Cremer et al. 2008, Brunsting et al. 2011, de Coninck and Benson 2014, Selma et al. 2014). Consequently, for example, CCS technologies have not only largely disappeared from the current agenda of politics and industry in Germany as a result of the costs and technical uncertainties, but, in particular, because of the rejection of the general public at this point in time, although, according to the scenarios portrayed by the IPCC (IPCC 2014), they are of central importance for compliance with the two-degree limit (Delgado, Lein Kjolberg and Wickson 2011, Apt and Fischhoff 2006, Cremer et al. 2008).

With this in mind, in addition to the topical fields of ecology and economy, the IASS project also took aspects of communication into account and dealt in this third sub-project with several questions and tasks:

1. How can information on CCU be conveyed free of valuation?

2. How can dialogues on CCU technology, which make a pertinent discussion of pros and cons possible, be initiated and led?

3. How is the technology for CO_2 utilisation perceived and evaluated by stakeholders?

4. What strategic thoughts on communication, as regards CCU technology, can be derived from possible evaluation patterns?

The sections 6.1 and 6.2 describe the communication formats developed and implemented within the scope of the project. In section 6.3, the results of the research work on questions 3 and 4 are presented.

[26] Naming these examples does not constitute any assessment or contextualisation of the named technology.

6.1. Initiation, accompaniment and observation of dialogue-oriented events together with diverse stakeholders of CCU technology

The work with diverse stakeholders is an important component of the IASS project work and was composed of several elements:

- Expert workshop on public acceptance of products with improved environmental properties
- Round Table events with participants from the economy, politics and society
- Introducing the topic of CCU at public events
- Answering questions from the media and others

The events implemented in the course of the project will be described in the following.

6.1.1. Workshop: Public acceptance of products with improved environmental properties

When technical innovations are introduced to the market, public acceptance of such technologies and products is a decisive factor for success. The complexity of the evaluation of the corresponding problems, however, often leads to a lower degree of consideration in the innovation process. The general public, for this reason, often perceives communication failures with regard to innovations. One example for this is the fuel E10 (Hauke 2014).

With this in mind, an expert workshop took place on the topic of "Public acceptance of products with improved environmental properties" within the scope of the CO_2ntext project in February 2014. The IASS invited representatives of selected companies to Potsdam in order to find out more about their experiences with introducing new products and technologies with improved environmental properties. Among those present were representatives from middle- and large-sized German companies. The goal in particular was to start a discussion on the experiences of the participants and what could be learned from them, and consequently how societal and public acceptance of ecologically sensible innovations can be promoted.

The results of this event were put together into a compilation by the IASS project team: the core propositions expressed within the context of the discussion were by no means consensual statements of all participants, but rather the results of controversial discussion. On the basis of the individual perspectives of the participants, the positions shown in the following draw attention to dimensions of problems which result in practice during the development, implementation and market introduction of products with improved environmental properties (Question 1). On the basis of these individual experiences, however, objectifiable indications were developed during the discussions which allowed for conclusions on conditions that could simplify or provide support in the future within companies and in interactions with politics and society – i.e. could aid the successful introduction of corresponding products (Question 2). All statements have to do with products which display clear environmental advantages in comparison to conventionally manufactured products.

I. What factors provide obstacles to successful market introduction of products with improved environmental properties?

- **The existing labelling for better environmental properties in products is currently only applicable on a limited basis.**

In business to business sales (B2B) ecological product information is essential if a new product is to be positioned on the market as "sustainable". In this regard, life cycle assessments (LCA) as well as existing certificates and labels are useful tools. These tools were not, however, always considered helpful when it came to public acceptance of the corresponding products for the final consumer (B2C). Accordingly, for example, products manufactured from recycled substances and accordingly labelled might possibly be perceived as inferior.

Ecologically advantageous product properties were seldom evaluated by participants as being decisive for buying. For this reason, such properties cannot, as a general rule, automatically lead to the higher prices being demanded in order to compensate for the additional efforts required by the technological change and certification of the properties in question. In particular, the high costs and the expected benefit of an LCA for final products did not tend to tip the scales in favour of profitability for smaller and medium-sized companies – LCAs could not become established in such areas for that reason and, consequently, could only be applied to a limited extent.

Environmentally related product properties often have to compete with other properties when it comes to the buying decision.

"Brand defeats measure": The experience of the participants showed that the consumer was quite able to trust the products of a strong "green" brand in the B2C sector even without a stamp of approval or data from a LCA. As a reverse conclusion, ecological measurements are important for conventionally positioned product brands, but are not a guarantee of plausibility for the consumer. LCA or other methods for the assessment of environmental properties could possibly offer additional points of attack, as long as across the product spectrum and across brands concurring terminology is not used.

"Emotion defeats price – price defeats sustainability": If other aspects such as the feelings connected to a brand are brought into the equation – according to statements of the participants, this is the only aspect which could beat a low price – then environmentally related properties would also be the least powerful point for participants.

Overall, environmentally related product properties were classified as being of limited relevance for the sales process.

Internal conflicts of goals can hinder ecological innovation processes

When developing more environmentally friendly products, it was important to place emphasis on individual environmentally relevant properties, according to the experiences of the participants, due to the fact that realistic efforts will not generally fulfil the highest ecological demands in every respect. Moreover, with regard to creation of LCAs, priorities were set through the respective premise of each assessment, for example, resource efficiency versus carbon footprint. In addition, conflicts of goals from other fields could have a negative influence on the development and introduction to the market of products with improved environmental properties, for example, maximisation of margins versus constituent parts from recycling processes, desired positioning of other properties versus positioning of ecological properties.

Perfectionism can be an obstacle to the introduction of ecologically improved products.

Ecological labels and other environmentally related certificates are often partly perceived as an expression of perfectionism, with which sustainable innovations have been particularly confronted as early as the development phase. Such demands on change can provide obstacles to implementation and later also affect dissemination: In one regard, an ecologically perfect product as an objective can be an internal obstacle when it comes to the development of products which are only designed to improve one or several environmentally related aspects while maintaining familiar standards in others. However, conversely, weighing up all the various product properties in an LCA is difficult to impart plausibly to the final consumer. Products which are only partly improved can quickly be perceived as "false labelling" or "greenwashing".

▪ Market research can inhibit ecological innovation.

Classical market research with the final consumer was considered inappropriate for technological innovations and could have inhibiting effects. This was due to the fact that particularly revolutionary and successful innovations would not allow for prognosis of their success; consequently, market analysis cannot be said to have foreseen such success. In addition, very innovative products awaken a need in the consumer which did not appear to exist before the actual introduction. Despite this, market research results in companies are still a necessary argumentative form of support for the introduction of new products. If a customer need cannot be perceived in the data collected, then the innovation might already run into difficulties in the early stages. This is particularly the case with environmentally related improvements.

▪ Conventional sale structures can be an obstacle to ecological innovation.

Prior to the introduction to market, it is not the final consumer but other disseminators who decide on public acceptance of innovations with improved environmental properties. Internal and external decision-making instances such as sales or trade departments often declare "the customer" to be putting the brakes on innovation. Assertion of innovations could be complicated in such cases and could, for example, require intensive training in sales. The strong power of established trade structures and their focus on the size of the turnover can also prove to be obstacles for environmentally related innovations.

Ecological innovations often did not fit into existing marketing and sales concepts. Customer typologies based on market research and sales experience frequently left no leeway to find more distinguished ways of approaching potential customers.

II. Can innovations with improved environmental properties be fostered during development and introduction to market?

▪ Creating standardised parameters and conditions and additional motivation to buy

As regards sustainable economic principles, the participants argued for the creation of ecological minimum standards and for the expansion of factors of motivation in accordance with the principles of reward, beyond existing standards. This was regarded as sensible on the basis that the improvement of environmental properties by product groups could also lead to a general usefulness for society as a whole. A combination of obligatory, applicable minimum standards with additional factors of motivation could lead to products with improved environmental properties becoming better established in competition with conventionally produced products and, in the future, help them to play a greater role in changing the behaviour of producers and customers.

▪ Sharing knowledge for sustainable innovations

It was viewed as a conductive attitude not to consider the implementation of environmentally related technology simply as a competitive advantage for an individual company or market product. Furthermore, in individual cases at least, discussions were held on the creation of "Open Innovation Networks" for joint innovations in industry. If innovations for improved environmental properties were introduced to the markets in cooperation, no individual manufacturer would be required to carry the risk alone. Experience has shown that the introduction of ecologically oriented product changes can, under certain circumstances, even make the manufacturer vulnerable. If common steps were made on the way to more sustainable products and, in this regard, generally towards more sustainable economic methods, the entrepreneurial hazard would be reduced, the plausibility on the market would increase, as would the profit for society: the general benefit of such technology would be greater through acting in cooperation, under the condition of the sustainable effects gained through its use.

▪ Promote environmentally related consumer needs

With a view to the holistic objectives of technologies with improved effects on the environment, it might perhaps be necessary to awaken previously unknown needs on the market – for example, through interim products for final customers. Communication, in this regard, plays a central role as does the previously mentioned creation of external parameters and conditions. Moreover, more sustainable decisions from final consumers can be stimulated and steered more strongly through state incentives.

▪ Make parameters and conditions possible to plan

The point in time of the introduction of environmentally related innovations is a decisive factor for their success. A lack of parameters and conditions (e.g. adaptations of recycling regulations), or even just a lack of public consciousness in the decisive moment can, in the end, create unsurmountable inhibitions for the establishment of products with improved environmental properties. Acceptance of an innovation among opinion leaders and decision makers is a basic condition for the successful way to market as well as the emotionally influenced decision to buy on the part of the final consumer.

It is important to remain informed of aspects related to perception and maintain close cooperation with legislative needs in order to make the legal-marketing and communicative-societal parameters and conditions of the innovative powers easier to plan.

▪ Common communication can promote innovation.

In order to successfully communicate products with improved environmental properties, the participants evaluate a unified understanding of terms such as "environmentally friendly", "sustainable", or "green" as being of great benefit. Even if various definitions, more or less with the same meaning, are used, there is a risk that varying or inflationary usage of such terms and communication could pose a great hazard and be a possible point of attack. In addition to transparent terminology, standards for clear non-misguiding, joint communication should be created and heeded.

Successful communication for products with improved environmental properties could, according to the participants, include more daring strategies. To simply concentrate on carbon dioxide limits is viewed as an insufficiently broad perspective and could be perceived as a "fixation on CO_2 emission". For this reason, other aspects such as resource efficiency or production-dependent environmental burdens should also be treated as foreground matters. These would generally have already been taken into account but are currently not as strongly perceived. Moreover, the source of the raw materials played an increasingly important role.

▪ Thinking in objectives

The prerequisite for a successful implementation of sustainable innovations is holistic, intersystemic thinking, according to the participants. During a long and difficult development and implementation process, mid- and even long-term objectives would still have to remain in focus. This aspect was often lacking in companies. Ultimately, the definition of utilisation of immediate profits was necessary for sustainable innovations, even if many ecological improvements also created increases in efficiency and, therefore, served to save costs.

One common conclusion of the event: the question of whether technological innovations could become reality depended greatly on individuals having the courage to assert clear ideas within institutions even in the face of resistance of others, while also managing to win internal and external stakeholders for their cause. Recognising such personalities and offering them support is a task which falls to companies, but also to society in general.

6.1.2. Round Table 1: "Can CO_2 be recycled?"

In June 2014, the next event followed: the first "Round Table CCU" at the IASS, under the leading question "Can CO_2 be recycled?" The goal of the workshop was to provide the participants with comprehensive information on the fundamental ideas and approaches of CCU technology as well as the funding scheme of the German government, current project developments and open questions of societal relevance. On the basis of the knowledge acquired, two discussion rounds on specific topics followed, consisting of discourse between a small podium and the further participants concerning aspects of closed-loop recycling management as well as the ecological potential that could result from the application of CCU technology.

Particularly diverse and fruitful was the combination of guests from the CCU technology community, research bodies, BMBF and other guests without a direct relationship to CCU, but representing relevant societal perspectives – for example, the Umweltbundesamt (Federal Environment Agency), the Deutsche Bundesstiftung Umwelt (German Federal Environmental Foundation), the Bund für Umwelt and Naturschutz Deutschland (B.U.N.D., Friends of the Earth Germany) and the magazine Öko-Test.

Due to the fact that the event had a predominantly informative character, serving to initiate open dialogue, no theses or position papers resulted from the first Round Table. As tangible output, the visual protocols[27] are available; these pick up on the important threads of the discussion and reveal possible relationships between them. Prior to the Round Table, a workshop booklet was created[28] which contained a first version of the Fact Sheet CCU (Olfe-Kräutlein et al. 2014) and introduced to the work performed at the IASS on the topic of CCU.

Following the event, comprehensive articles appeared in the magazine Öko-Test (Lasch 2014) and in the newspaper "Die Zeit" (Schramm 2014) on the subject of CO_2 recycling. Although the event was not accompanied by active press relations, the Round Table was inspiring for the topic of CCU and articles found their way into two important media outlets.

6.1.3. Round Table 2: "CO_2-Recycling – Option für Politik und Gesellschaft?" (Option for Politics and Society)

In November 2015, the IASS continued the "Round Table" format, this time under the leading question "CO_2 Recycling – option for politics and society?"[29] The focus of the second Round Table was less on informing the participants; instead, the introduction of the topic was limited to a short lecture. The event took more time to discuss relevant interfacing topics such as the role of CCU technology in the turn of energy policies, as well as questions on communication of CCU and matters of closed-loop recycling management related to CCU.

To promote the character of dialogue and motivate the guests in the best possible way for content-related contributions, the event did not have a panel. Instead, for each topic, three to five guests, explicitly also people without special professional knowledge in the CCU field, but with other relevant expertise, were requested to deliver a short impulse statement, which the moderator integrated in the course of the discussion.

Prior to the Round Table, the project team worked out a draft for 12 theses on societal and political importance of CCU technology. This draft was given to all participants as well as all project partners in advance of the event with the request for comments. It was on the basis of these comments and the input received during the event that the final version of the theses was created and published in December 2015 (Naims et al. 2015).

[27] These visual protocols can be found as illustrations at the beginning of the chapters 1,7 10 and 11.

[28] http://www.iass-potsdam.de/sites/default/files/files/ccu_ly_workshop_booklet_140603_digital_0.pdf. Accessed 25/10/2016.

[29] http://www.iass-potsdam.de/en/node/2335. Accessed 25/10/2016.

In addition, during the event, short statements of the active participants were recorded and published on the website[30] in the dossier on CCU technology.

6.1.4. Further public relations work

The project team actively participated during the entire course of the project at public events, for example, at the "Woche der Nachhaltigkeit" (Week of Sustainability) (June 2013) and at the series "Bildung für nachhaltige Entwicklung" (Education for Sustainable Development) (February 2015), both of which took place in Potsdam. The many diverse questions which arrived from the press were professionally answered or forwarded to the corresponding experts.

6.1.5. Dialogue-oriented stakeholder work on CCU: Input and Output at the same time

All in all, the described dialogue-centred measures allowed us to address the various stakeholder groups: academic and industrial professionals, as well as political and societal representatives of various interests as well as, directly and indirectly, the general public via the media reports. The project team at the IASS gained deeper insights into extremely varying perspectives of CCU technology, in the form of views, arguments and opinions which would not have become clear or visible without the intensive work with the stakeholders, due to the fact that these matters were not well covered in the media or professional discussions. The outcome of the intensive work with stakeholders is therefore not simply a surplus of information for specific target groups, but includes very concrete instances of input and an increase in knowledge for the transdisciplinary work at the IASS.

6.2. Making information material available and building an information platform on CCU technology for laypersons

One goal of the subproject "Communication" was the conceptualisation and primarily internet-based dissemination of advertisement-free, informational material, free of evaluation, on the possibilities and limits of utilising carbon dioxide. To this end, the IASS format "Fact Sheet", a six-page leaflet on CCU technology, was published and a web platform was conceptualised and set up.[31] For the web platform, the project team developed the wording "co2inside" as a website URL, claim and logo, considering that the creation of a memorable generic term for all areas of application would be useful.

6.2.1. Content of the web platform

The web platform co$_2$inside directs the user to relevant information on possibilities for the use of carbon dioxide, by considering the perspective of the visitor and – besides a short overview (**"raw material CO_2"**) – asking three central questions. As a first answer, short texts present fundamental information in logical arguments in a broadly easily understandable fashion, free from evaluation. In line with the philosophy of the platform, co$_2$inside links to further information on other, primarily external, information sources. The three central questions which are asked will be introduced in the following:

"Funktioniert das?" (Does that work?) In order to answer this question, the general functional schema for CO_2 utilisation is described, subdivided into physical and material utilisation, under the bullet "technology". A graphical overview follows (see Figure 2, Chapter 2.4.) on various ways of utilising CO_2, which explains the entire cycle from the CO_2 extraction up to the options at the end of life – examples are used and optical references are made to existing gaps on the way to creating a cycle. The menu item "CO_2 sources" addresses the question of the sources of the CO_2 to be used. Here, the sources which can be considered for the utilisation of CO_2 are described: CO_2 as a by-product of chemical processes, CO_2 won from the filtering of flue gases, as well as from previously emitted CO_2 in the atmosphere.

[30] http://www.iass-potsdam.de/de/content/co2-vom-abfall-zum-rohstoff. Accessed 25/10/2016.

[31] http://www.co2inside.de. Accessed 25/10/2016.

"Ist das nützlich?" (**Is that useful?**) This question is addressed from an ecological and an economic perspective. The bullets "Ecology" and "Life Cycle" describe currently predictable possible effects on the environment as a result of implementation of CCU technology and explain the Life Cycle Assessment (LCA) as the method of choice, in order to evaluate possible environmentally related effects throughout the entire life cycle of a product. Under "economy", finally, possible advantages and disadvantages of the implementation of CCU technology are described.

"Perspective CO_2?" The menu item "Perspective CO_2" links to the largest research programmes on CO_2 utilisation ("Research"), as well as, under "Kreislaufdenken" (thinking in closed loops), to the possible role of this technology within the scope of the development of closed-loop recycling management, as well as the thinking and way of life necessary to make this possible.

In addition, the web platform has a **download area** in which publications on CCU technology are made available, currently only publications from the IASS.

6.2.2. Design of the web platform and development of the logo

As is often the case for technical-scientific research topics, working with images for CO_2 utilisation is generally unfavourable. Chemical processes can, of course, be presented as images; however, these are, in part, difficult to understand or do not have any concrete relationship to CCU technology. One example for a less plausible illustration is CO_2 as a gas, which is transparent but is often presented in the form of sooty waste gases coming from industrial chimneys. In addition, usable images generally came from industrial representatives and would potentially have contradicted the basic principle of an advertisement-free information platform. In order to solve this problem, an abstract design was chosen with a clover leaf in front of a dark background. This form is also used to cover the four topic areas in the navigational structure (see figure 6).

The co$_2$inside logo developed for the web page (see figure 6, upper left) offers visible recognition properties for CCU technology and products. The chemical

Figure 6: Welcome page of the web platform www.co2inside.de

Source: www.co2inside.de

symbol in the circle transports, on the one hand, the property of CO_2 as an ingredient while, on the other, it also creates an optical connection to the topic of cycle/closed loop recycling management.

6.2.3. Perspective

The web platform co$_2$inside is currently a basic offer which allows laypersons low-level access to the topic of CO_2 utilisation. This offer could be worked on and improved in various regards.[32] In one respect, the information contained can and must be updated and supplemented, in another, the concept of a platform with interactive elements, such as a forum or a blog, could be further pursued and extended. The neutrality of the information is the unique property of the offer and makes the platform a point of reference for all societal organisations that are looking for objective information on CCU technology and its assessment.

6.3. How is technology for CO_2 utilisation perceived and evaluated by stakeholders?

6.3.1. Communicative potential of CCU technology from the perspective of communication professionals within the chemical industry

Within the scope of a stakeholder analysis, from the year 2013 onwards, several interviews were carried out with communication professionals in the chemical industry. “Stakeholders” are those individuals and groups that have material or immaterial claims towards any organisation and who have a reciprocal, multifaceted relationship of influence with that organisation (Freeman 2004). This relationship of influence can, though must not, include economic aspects. Communication experts in chemical industry companies that are developing CCU technologies, and in chemical industry associations, have complex relationship structures within their organisations as regards the topic of CCU technology. Due to their function, it is possible to assume that they have a decisive impact on the positioning and development of CCU technology as a communication topic and, therefore, are influential stakeholders also in the development phases before the introduction to market.

In order to identify the responsible contact persons within the various large organisations at the point in time of the interview or in the future for communication on CCU technology, the press office of the manager of communication was then contacted and enquiries were made as to who the “communication expert with responsibility for the topic of carbon capture and utilisation” might be. With the goal of, on the one hand, to be able to evaluate the communicative potential of CCU technology from the perspective of those responsible in industry and, on the other, to identify factors which could indicate unknown problems and challenges from the communication perspective (partly in early stages of development), five interviews were held in August 2013[33]. Three of these took place directly in companies working in the chemical industry, while two were held in a corresponding professional association, respectively and separately with those responsible for the topic of CCU and the press spokesperson. The conversations primarily had an exploratory character that followed the three basic questions:

- How would you describe the current public reflections and evaluations of CCU technology and products?

[32] A content-related expansion and an optical reworking of the web page www.co2inside.de are planned for the duration of the project CO$_2$NetPlus. The IASS works together with the DECHEMA and the Wuppertal Institut in an accompanying scientific project for the new sponsorship programme of the BMBF; compare http://www.chemieundco2.de/. Accessed 25/10/2016.

[33] The interviews lasted between 30 and 90 minutes and were digitally recorded. Due to the fact that all interview partners were promised anonymity, all quotes will be presented anonymously. Labelling with letters makes allocation to the diverse interview partners possible.

- Can you name obstacles for highly promising/successful communication? Can you identify strengths?

- Which future perspectives and which potential do you see?

The integration of communication aspects in research and development processes, sustainability as criteria of communication, and plausibility in communication in the chemical industry remain the subject of continued discussion.

Explorative interviews with a small number of interview partners do not deliver any statistically resilient proof or significant findings for future communication. They do, however, from the perspective of those involved in communication, offer important indications to predictable, possibly problematic aspects of communication, as well as useful, potentially positive, aspects of communication of CCU technology. It is extremely important at this point to note that these indications are always to be considered as statements **on communication**. They do not allow for judgements, for example, on whether the implementation of CCU technology is to be considered “safe”. This assessment must be evaluated individually according to application by industry, and checked by the relevant institutions. The indications contained in the interviews do, however, make a statement on the aspect of safety as a communication topic which is most likely positive, as seen by communication experts; therefore, this statement could be used in future communication strategies by companies, associations, or in politics. Negatively evaluated aspects of topics could be identified early and addressed in just these strategies.

6.3.1.1. Identification of communication-related strengths of CCU technology

“At the moment we are in the hooray phase.”(a) Questioned on their evaluation of the general tone of media reports, the respondents had an overall positive picture and evaluated the ability to reach consensus on the topic of CO_2 prevention as conducive. “The time has come. The people know that CO_2 cannot be chucked out for ever.”(b) Besides the right point in time, the topic of CCU technology was attributed fundamental suitability for communication: “The fact that carbon dioxide is usable is of course a great topic.”(b) and “the topic is simply sexy.”(c) A growth in interest was also noticed: “In communication, the topic plays a role in the scientific community, but also beyond that community. The colleagues in the press office are receiving queries regularly.”(c) The respondents were also in a position to name specific positive communication-related properties. They attributed a lack of risk to the technology, due to which they do not reckon with communication problems: “There are no hazards to be seen.”(c) or “If it has to do with a special chemical that the consumer never comes into contact with, then that is not addressed in the communication.”(a) Sustainability as a driver for CCU technology was also seen as a communicative advantage: “Even environmentally driven NGOs are interested in seeing someone find something that can be done with CO_2. ... It is possible to create public acceptance for it.”(a) and “The trend is moving towards green, sustainable products. That’s something for a good conscience. The consumer might possibly pay a little bit more or the same and then they’re happy that they’ve bought a “green product”. Green products are the current trend, hopefully green plastics too!”(b)

6.3.1.2. Identification of communication-related weaknesses of CCU technology

A weakness in the communication was seen by the respondents to be, in particular, the proximity to “Carbon Capture and Storage” technology (CCS), manifesting itself in technical, but also in semantic regard: “Negative voices could spread the message that CCS technology is being supported by sponsoring capture and power plants.” (b) and “The term CCU is one I don’t like, because it is automatically married to CCS. In all circumstances, I would attempt to decouple it from this CCS discussion. ... There is the danger that everything will be tarred with the same brush.”(a)

Moreover, ecological aspects seem to be evaluated as risky from a communication perspective. While the respondents, on the one hand, recognise positive potential here, on the other, they saw hazards in the suspicion of “greenwashing”; another hazard was seen as a player being on the same team as industry, who are trying to promote their products as more environmentally friendly, more ecological, useful, or sensible than they actually are: "In the choice of the brand name there are also stumbling blocks. Let's just assume that the word "green" is included in the name. I can imagine that the diverse NGOs would go on the rampage and start asking: 'What is green about that?' And then you are automatically in a discussion that's not going to be easy." (b) Application-specific, ecologically irrelevant aspects, for example raw material and energy consumption and product-specific recycling options, were also seen as potential controversial points of public discourse: "We need a lot of energy to process CO_2. The invoice for this has to be opened up. The public don't want to be opening it at the moment, but they will do it at some point. Then renewable energies will play a role."(c) and "There's still the question of recycling. We can only say that we are parking the CO_2 for a specific duration. They're going to realise very quickly that it gets released again during incineration."(b)

New technologies which might include risks for the community, but are hardly subject to public control, and at the same time do not offer any visible benefits for users, are more often the subject of acceptance problems (Renn 2005). Such a conflict of interest between industry and the general public was also anticipated by the communication experts: "And there you see the 'citizen against everything' phenomenon. How do we get the transparency? How do we create confidence? Particularly in the case of phenomena such as Stuttgart 21 or the Berlin airport, you can see what happens really quickly if you don't take people's opinions on board, and the kinds of problems that can occur." (d) Generally, the chemical industry was evaluated as a potentially problematic communicator: "When we build plants, there's always the hazard that someone will start to oppose it." (b) or "Someone comes along and says: 'That's hazardous, that's under high pressure, something can escape from there.' ... Chemical products simply offer a greater potential for hostility."(b) Or more generally: "Every company has specific opponents who will try to find aspects with which they can cause damage."(b) The technical complexity of the topic could also be a barrier for communication: "The biggest problem with regard to CCU technology or CCS is that it is not really understood – what is really going on? Where are the chances, where are the challenges and problems? It is not clear for all of the target groups."(d) False understanding that could lead to rejection: "The technology will be doubted." (a)

Generally, scepticism was expressed as regards the importance of the topic: "The topic is not relevant enough. You can compare that with crude oil today: Nobody is interested in what their scarf or their yoghurt container are made of. It is all based on crude oil, and only about 10% know that. That's also the way I see it with CO_2."(c) The respondents evaluated the relevance of the topic as low: "(CCU) doesn't have the same emotional power. It is too technically driven. Technical hurdles are there to be overcome, so that the people will start to take an interest in it. It is not done with a single instance of communication. Various communication channels have to be used in order to promote the topic. ... It will always remain a niche topic."(d) or "You can't just say, I'm going to save CO_2 here, and do a quick LCA on it, but if there seems to be absolutely no benefit for the customer, then I have to ask myself: Why am I doing that in the first place?"(d) One of the respondents, in this context, drew attention to the discrepancy between the view of oneself and the view of others: "The company thinks it is the axis the world turns around. Communicators in companies and in the rest of the world often speak another language."(b) This gap in understanding could result in rejection: "Utilisation of CO_2 remains a niche application. In the mid-term, we will not be creating our large-scale plastics with it."(c)

Finally, the respondents identified diverse approaches and timelines in research and development processes and in the media as potential problems for communication activities: "It is being repressed that It is going to take time to develop these things. The people might well lose interest."(c) or "we have talked about it internally. It doesn't make any sense to talk about it outside... We are talking about platform technologies with which we will be entering the market in five to ten years."(d) In this context, fundamental doubts in the suitability of CCU technology as a media topic were expressed: "If I look at the topic, I ask myself: is it interesting? Moving? Useful? If you look at the topic of CCU, as far as relevance goes, it is very difficult to communicate, and externally we can answer that very easily."(d) It seems sensible, therefore, to adopt a moderate approach to the communication of CCU: "At the moment, I see it as a communication opportunity, if we don't awaken too many expectations."(b)

6.3.1.3. Interim conclusion: Branch-specific perspectives of the chemical industry itself

Even where the individual backgrounds clearly influence the perspectives of the respondents, it is still possible to recognise **common strengths and weaknesses of communication aspects of CCU technology**. The respondents identified the characterisations "technical progress" and particularly "attractive" as positive areas of topics for the communication of CCU technology, proven with such attributes as "zeitgeist", "simply a great topic", "unique", "sexy". A further positive frame of topics is "safety", due to the fact that the experts did not ascribe any important technical risks to CCU technology. Ecological aspects, on the other hand, seem to represent a more ambiguous range of topics. Positive attributes such as "fewer CO_2 emissions" and other sustainability relevant aspects are seen as communication opportunities; however, this is accompanied by the fear that the representatives of the chemical industry could be accused of greenwashing in such communication. One clearly negative range of topics is the semantic and technological proximity to CCS technologies; these are to be avoided wherever possible, according to the view of the communication experts (please also refer to chapter 8.).

The degree to which these indications from the sector are in agreement with the perspectives of a wider stakeholder group is explained in the following section 6.3.2. Section 6.3.3 discusses the possible implications of these indications for future communication of CCU technology.

6.3.2. Assessment of critical aspects of CCU technology by diverse stakeholders within the scope of a discursive event

Within the context of dialogical work in the project CO_2, the IASS invited participants to a Round Table with the title "CO_2-Recycling – Option für Politik und Gesellschaft?" (CO_2 Recycling – Option for politics and society?) in November 2015 (for further information on this and other events see Chapter 6.1.). Three rounds of discussions with short impulses from IASS employees, experts from the fields of politics, and interested associations and NGOs were dedicated to the following topical fields: CCU and the turn of energy policies; communication and closed-loop recycling management. The rounds of discussion served, on the one hand, to create exchange between the stakeholders while, on the other, to enable observations on the part of the host with regard to the threads of argumentation of various stakeholders. The threads of argumentation which will be presented in the following were documented by the project team (please also refer to http://www.iass-potsdam.de/en/node/2335). They are derived from the discussion rounds on communication entitled "Chance oder Hindernis? Kommunikation für CO_2-Recycling" (Chance or Obstacle? Communication for CO_2 Recycling)[34], and cast light on aspects of communication of CCU technology from the perspective of varying stakeholders from economic, political and societal interest groups.

Although over the few last years some articles have already appeared in diverse media with regard to CO_2 utilisation – and there does seem to be a general increase in reports on the potential uses in connection with it – the topics related to this field of technology are less visible in public discourse. The existing media reports could, however, be an important influencing factor in the course of public and organisation-internal discourse.

[34] Short inputs from: Dr. Barbara Olfe-Kräutlein (IASS), Dr. Christoph Steinbach (chemical Nanotechnology, DECHEMA e. V.), Timo Bovi (Senior Consultant, Johanssen + Kretschmer Strategische Kommunikation GmbH), Tilman Benzing (energy, climate protection and resources, raw material policy, Verband der Chemischen Industry e. V.).

Accordingly, on occasion, the role of journalists was controversially discussed. The assumption that journalists tend to communicate maximum scenarios without exercising the necessary care, and, therefore, awaken false expectations, was contrasted with the premise that press officers of institutes and companies often anticipated the behaviour of the media in selecting topics and exaggerated their own communication, partly in similar ways.

A further hazard in the communication of CCU technology lies in the fact that, **for the risk assessment, unsuitable studies** are often used or the explained risks are disproportionately evaluated and presented by laypersons.

The participants regard the choice of terminology as decisive for alignment and for the understanding of CCU technology. In particular, the **semantic proximity to CCS** is seen as a communicative hurdle for CCU. It was argued that the term CCU is laden with communicative risks because CCS already has a negative connotation in Germany. The usage of a neutral term such as "CO_2 recycling" instead of CCU was, in contrast, evaluated as more advantageous. Again, it was mentioned that the role of energy could be important in communication. The term "utilisation as materials" of CO_2 could be useful in order to distinguish it from the "energetic utilisation" of fossil energy sources. Another topic that was raised again during the discussion of terms was "more efficient" or "more sustainable" ways of dealing with resources as well as "efficient carbon recycling".

In general, the communicative context of CCU was perceived as "extremely large" and multifaceted. Parties in communication for science and economy have a difficult task, as do the reporting media with regard to the **contextualisation**: Arguments on climate protection should not be foregrounded if climate protection is not the actual topic. An example here: a report on CCU was published in the Handelsblatt under the headline "Kampf ums Klima" (fight for the climate) (Fröndhoff 2015). During the round of discussions, there was general agreement that the issue of climate protection was neither the original motivation nor the primary potential of the development of CCU technology; therefore, this topic should be communicated carefully as a subordinate aspect of CCU.

The links between the topics, however, pose a challenge, in particular due to the close connection between the flue gas CO_2 and climate change, which renders it difficult to avoid any link to climate change in the pertaining communication.

Is it at all necessary to communicate CCU? A debate took place on whether CCU technology should be communicated only once the use of the technology has led to products becoming better or less expensive. Consequently, the question developed on the degree to which active communication on raw materials should take place if they are not anyway in the minds of the general public. Another challenge observed was the great potential of CCU, for example, to promote the notion of extension of the resource base, provided this is not perceived as a problem for society. Finally, the observation was made that no Communication was no solution: **We cannot simply *not* communicate.** Given the fact that active communication is always governed by interests, who speaks and with whom, plays a decisive role.

Another topic of discussion that was regarded as important was the question of whether communication problems might, perhaps, generally be the greatest hazard when introducing CCU technology – in particular the danger of the accusation of **"greenwashing" on the part of chemical companies**, thus, a conscious or unconscious attempt to portray ecologically ineffective technology as "green" technology.

6.3.2.1. Interim conclusion: perspectives of various stakeholders as regards CCU

As was the case in the individual interviews with representatives of the chemical industry, individual statements of stakeholders do not represent resilient proof of communication. What they do, however, is show which threads of argument might occur in discussions and dialogues around CCU and can, therefore, in particular when compared and contrasted to the content of the individual conversations (please refer to Chapter 6.3.1.3.), be regarded as indicators for aspects of communication that communication strategies should take into consideration and address in the future.

In general, the discussions with technical experts in CO_2 recycling and participants from other relevant areas, for example the magazine Ökotest, the Deutsche Umwelthilfe DUH or the Umweltbundesamt (Federal Environment Agency), were extremely interesting. It is worth mentioning the lively meetings between representatives of an NGO and CCU experts from areas of economy and politics. In retrospect, the participants viewed the discussions in these constellations as particularly educative since such discussions seldom or never take place within the scope of everyday business. The dialogue with these extremely diverse stakeholders revealed the following:

- There are only very few unified positions on the topic of CCU technology and, generally, these are only shared by technical experts from the community

- It seems to be the case that the respective backgrounds and perspectives of the diverse stakeholders tend to predominate and align them in their respective directions of travel

- CCU experts from the technical community have fewer points of contact for controversial debate in public

- They stand in contrast to the observed objections[35] of stakeholders from other fields

It was obvious that the advantages of the technology mentioned within the scope of the event[36] were insufficient to automatically preclude objections.

The various aspects of knowledge acquired from the discourse with representatives of extremely diverse interest groups makes it apparent how suitable such a format is as an event, in order to recognise individual positions and opinions – which can probably be generalised in part – and include these in other scientific analyses and in the development of corresponding communication strategies.

CCU TECHNOLOGY IN THE MEDIA

A media analysis collected and analysed media reports on the topic of CCU from the years 2012/2013 and 2015. The idea here was to reap knowledge on parties; mentioned projects and products; terms used; directly addressed positive and negative aspects or corresponding connotations; evaluations; portrayed risks; and general estimations. The media analysis is subject of a publication which is currently in the publication process.

[35] http://www.iass-potsdam.de/en/node/2335. Accessed 25/10/2016.

[36] http://www.iass-potsdam.de/en/node/2335. Accessed 25/10/2016.

Tables 5 and 6: A review of obstacles and chances in future communication of CCU technology, seen from the perspective of communication experts from the chemical industry (5) and participants of a dialogical event at the IASS (6)

Source: IASS

Communication opportunities from the perspective of stakeholders	Obstacles to communication from the perspective of stakeholders
■ Discourse is multifaceted – new terms for CCU processes could still be introduced.	■ Terms are a semantic hazard due to the proximity to CCS
■ Contextualisation of individual aspects can create terminological sovereignty.	■ Greatest hazard at the time of product introduction > perception of greenwashing.
■ No communication is not an option > use chances!	■ Consumers have had no contact with the product up to now.
	■ Unsuitable studies were used to reach judgements on the potential for danger.
	■ Contextualisation of terms can hold risks.
	■ Lack of raw materials is not perceived as a societal problem.
	■ Journalists use exaggerated scenarios which are being offered to them by press offices in anticipatory obedience.

Communication opportunities from the perspective of communicators in the chemical industry.	Obstacles to communication from the perspective of communicators in the chemical industry
■ Necessity of reduction of emissions corresponds with common sense.	■ CCU technology is technologically and semantically too close to CCS technology.
■ Technology is too far away from the consumer to become subject to rejection.	■ Users of the technology could be accused of "greenwashing".
■ CCU technology is not hazardous.	■ The topic will perhaps not be perceived by the general public as relevant.
■ CCU is categorised as an "attractive" media topic. The notion of recycling CO_2 is in line with the current zeitgeist.	■ The topic occupies the field of tension between industry and general public.
■ The topic is special.	■ The topic is too complex.
	■ The topic is too special.
	■ Respective logical frameworks of R & D and media are not in harmony.
	■ The products do not offer any functional added value for the consumer.

6.3.3. Conclusion: Recommendations for the further communication of CCU technology

While the questioned communication experts of the chemical industry tended to approach the topic of aspects of communication of CCU technology in a more strategic fashion and tended to weigh up the advantages and disadvantages in an objective fashion from a communication perspective, the Round Table was distinguished by argumentative exchanges of a more general nature, in part quite serious ones. In addition, structured conversation with the experts made it easier to work out a framework of topics and joint/contrary positions, while the contributions during the rounds of discussions were, of course, less structured and tended to offer individual perspectives and positions of the participants.

Comparison of the results from both communication methods, collected as estimations and opinions on the topic of CCU technology and communication, showed that commonalities were to be found in addition to these general differences.

The respondents from the chemical industry and the participants of the discussion event, which consisted of a wider professional and organisational range of backgrounds, identified the risk of suspicion of "greenwashing", as well as semantic proximity of CCU technology to CCS technologies, as obstacles for successful communication. In addition, both groups saw the **lack of points of contact with the consumer** as well as the lack of relevance with regard to the communication potential as weaknesses. Experts from the chemical industry seemed, in this regard, to be looking back on corresponding negative experiences: The "lack of points of contact" was also evaluated as a positive property of the topic of CCU technology (by the experts), due to the fact that a lower degree of perceived effect on the public would lead to less public rejection.

The **role of the media** was evaluated by both groups as problematic; of particular note here were the arguments of "differing logic", "too complex", and "exaggerated scenarios". The basis of the aspects named was identified as a fear of inappropriate media reception of the specific properties of CCU technology.

Although the respondents from the chemical industry see highly promising communication-related properties in CCU technology, including lack of risk, special nature, relationship to common sense, or zeitgeist, the comments perceived as positive in the rounds of discussion at the Round Table focused more on communicatively tactical properties. At this point, it would be important, in the opinion of the stakeholders, to use the chances offered by the lack of contextualisation to steer the discourse and influence it.

How will the evaluations of the respondents and the discourse participants affect the planning of future communication activities? The following **critical aspects** that any distinguishing communication strategy must address were named:

- clear terms and contextual delimitation to CCS technology
- the necessity of assessing different applications of CCU technology individually and communicating concrete ecological effects
- realistic presentation of the possibilities; however, in particular, also the limits of the climatic and environmental effects through implementation of CCU technology

In this regard, the goal is to prevent misunderstandings of possible environmentally related properties ("greenwashing)" through transparent assessment and corresponding communication.

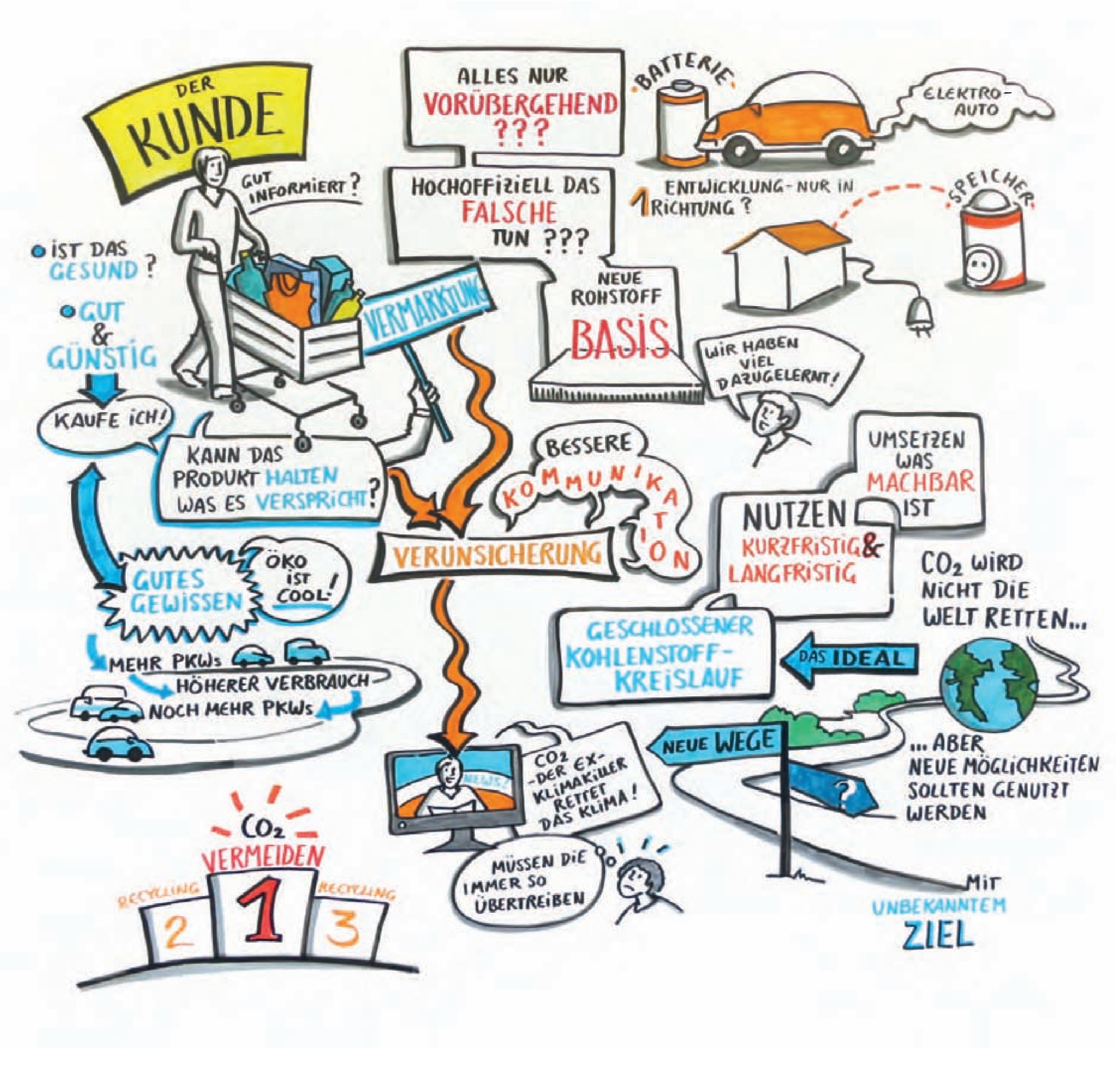
A further aspect to be addressed is the approach to **topical contexts and terms** which are not yet defined. In the CCU field, there is still no general terminology being used among industrial, scientific or societal and political players. The importance of this is not to be underestimated. First, associative bridges can be built with definitions of terms. It can, for example, occur that a recipient of information could understand the terms "CCU" and "CO_2 recycling" as completely different concepts although the communicator wishes to describe the same technological family with both. While CCU means little without further explanation and, with regard to terms, suggests proximity to CCS, "CO_2 recycling", for example, automatically creates an immediate, large-scale scope of reference to recycling processes and explains itself on a very simple level. The lack of precision in the usage of such a term, however, speaks in many ways against its usage (please also refer to chapter 7.).

The determination of general, analogously used terminology cannot be decided by a single party, and should, just like the contextualisation, be part of a joint communication strategy, for example, within the scope of a professional association. The categorisation of CCU technology on the part of the recipients will be influenced by the choice of aspects of CCU technology that are referenced and particularly emphasised. Does it primarily concern climate change? Does it primarily concern exploitation of new material sources? Do we need these to replace fossil carbon sources? Are we therefore acting out of an ecological motivation or is the motivation perhaps also political – i.e. one which will make the German chemical industry less dependent on oil imports? Even if the potential uses of CCU technology can be extremely varied, a common strategy of representatives in the CCU field could help to create a position and context.

The **responsibility** for the development of a basis for a joint communication strategy could lie in the hands of the individuals themselves, who are unified by further development and implementation of CCU technology. This common interest can be seen as a tiny common denominator, despite the fact that the individual interests are extremely varied in detail – not only due to the various sectors and areas of application, but also because of the variation in the societal roles and tasks of the involved NGOs, companies, scientific institutes, associations and political organisations.

The **goal** of a common communication strategy which takes the aforementioned points into consideration would be to promote an unprejudiced willingness to enter into discussion on CCU technology among the diverse stakeholders as well as within as wide a public debate as possible. This could, without serving individual commercial interests, be initiated, and under certain circumstances also partly jointly implemented, by representatives from politics, science and society, as well as industry and associations, jointly planned and coordinated, for example, in the form of an umbrella association or possibly something less institutional: a joint group for communication, possibly within the scope of existing association structures. The prerequisite here is transparency in all tasks at each and every point in time as regards the respective CCU applications, as well as cooperation based on facts.

It is recommended that there be a minimum of joint communication strategy, at the least, however, the development of guidelines on relevant terms and topical frameworks, in order to create, both nationally and internationally, the prerequisites for unbiased discussion of further promotion and implementation of CCU technology and to awaken societal consciousness for topics such as closed loop recycling management or recycling and new technological ways towards a more sustainable economy and society.



This illustration is a “Graphic Recording” of the dialogue event “Can CO_2 be recycled? A dialogue on Carbon Capture and Utilisation (CCU) Technologies” held on June 5th 2014 at IASS Potsdam. The drawing contains different patterns of argumentation and questions that shaped the discussion. See also chapter 6.
© IASS/Gabriele Heinzel Graphic Recording

7. Development of scenarios for labelling of CO_2-based products

Due to the approaching market introduction of CO_2-based products[37], the question arises whether and how the specific properties of such products can be imparted to possible consumers. In the case of labelling of product properties which are not only being communicated by individual suppliers on the market, a suitable method could be labels which are independent of manufacturers. A multitude of existing labels, certifications and designations can be considered for CCU products, such as, for example, the German "The Blue Angel/Der Blaue Engel". Therefore, in the first place, it is necessary to consider which options generally exist for environmental labelling of CO_2-based products, and to then find relationships between these and the possible properties and messages of products resulting from implementation of CCU processes.

7.1. Possibilities of environmentally related labelling of CO_2-based products

Generally, it is possible to distinguish between two types of certification that can be considered.

7.1.1. Labelling with a reference to the producing organisation

One possibility is a certification type which draws attention to the management of the aspects in which an organisation is actively responsible for the environment. A key subject of consideration in this case would be manufacture and product development processes. This category includes, for example, voluntary certification of the environmental management systems EMS[38] (such as ISO 140012 public environmental declarations[39]) or guidelines for consideration of environmentally friendly design of products, summarised under the term "Ecodesign" in ISO 14006:2011-10 (ISO 2006c). The corresponding guidelines are summarised in the functional report ISO/TR 14062 (ISO 2002).

[37] CO_2-products can be interim products or end products; please also refer to Chapter 4.

[38] EMS: Environmental Management System.

[39] http://www.emas.de/teilnahme/umwelterklaerungen/, [Accessed November 3rd, 2016].

7.1.2. Labelling related to the specific properties of a product, process or service

The second possibility is certification regarding the manufacturing processes of a product or specific product properties related to the manufacture. In this case, the manufactured interim or end products are themselves the subject of consideration. The environmental labelling and declarations described in ISO 14020 (ISO 2000) are also included under this type of certification. They can be subdivided into three different types.

Environmental labelling, according to **Type I** (DIN EN ISO 14024) (ISO 1999), designates products of a specific product category which have fewer effects on the environment than other comparable products, throughout their entire life cycle. These effects on the environment are measured in accordance with criteria determined by a third-party within a voluntary programme such as "Blue Angel/Blauer Engel" (see above).

A variation on this type is product labelling, which only takes individual environmental aspects, for example, energy or water utilisation, into consideration. They are, therefore, not as comprehensive in their significance as environmental labelling of Type I; however, they can make transparent and understandable statements on individual aspects on the basis of parameters and values determined by external instances. Some examples are to be found in Table 7 under the heading **"Type I like"** (UNOPS 2009).

Environmentally related manufacturer declarations, in accordance with **Type II** (DIN EN ISO 14021) (ISO 2016) describe declarations in which the manufacturers make their own statements, on their own responsibility, on the relevant environmental aspects[40] of products without verification of third parties. Assessment of the statements made with regard to the environment must at least be feasible on demand. The choice of criteria, in this case, is made by the companies in question or the relevant associations.

Environmental declarations in accordance with **Type III** (DIN ISO 14025) (ISO 2006a) include the results of a life cycle analysis (please also refer to Chapter 4). The environmental parameters to be reported and the format of the report are determined in the so-called Product Category Rules (PCR) by a qualified third party, under involvement of all participants, for example, relevant companies and associations, as well as environmental and consumer protection organisations or public offices or agencies. The environmental data and effects for the declaration are accordingly compiled by the companies. Although these are assessed by third parties, they are not evaluated and no judgement is made on them. Comparative, evaluative categorisation of the results is thus left to the user. In order to simplify this for the user, the ISO Standard includes rules for the presentation of results which are designed to make it possible for laypersons to compare varying products and parameters (ISO 2006b).

In addition, there is a multitude of other labels and designations which do not correspond with the ISO regulations, and for that reason cannot be allocated to any of these categories.

[40] What distinguishes an 'environmental aspect' from 'environmental impact'? An environmental aspect defines an aspect of action, products or services of an organisation which has effects on the environment. Such environmental impact is any positive or negative change to the environment, in whole or in part due to action, products or services of the organisation; cp. http://www.emas.de/fileadmin/user_upload/06_service/PDF-Dateien/indirekte_umweltaspekte_umweltmanagement.pdf.

Types of environmental labels

Figure 7: Examples of varying types of environmental labels

Source: Lorente Lafuente

7.2. Remarks on the significance and the properties of environmental labelling and declarations

Generally, during the development of environmental labelling and declarations, all relevant aspects, along the entire life cycle of a product, should be included. The extent to which this actually happens varies, however, depending on the type of environmental label or declaration, the type of statement, and the product category (ISO 2000). In the calculation of effects on the environment for labelling of Types I and III, the method described in ISO-14040- (ISO 2006b) and ISO-14044-Standards (ISO 2006c) must be used ("life cycle assessment", please also refer to Chapter 4). For self-declarations (Type II) this is not mandatorily necessary (ISO 2016). However, environmental declarations according to Type II can, in the same way, lead to a transparent, valid result, as long as understandable and verifiable evaluation parameters are used and revealed.

As described in the previous sections, the individual types of environmental labelling fulfil differing needs and vary considerably in their practicability and benefit for the consumer. With regard to possible designation of CCU products, plausibility, verifiability and credibility are particular relative properties of any labelling system, due to the fact that environmentally related labelling is a tool of informational policy in the B2B and in the B2C sectors. Environmental, health, and climate compatibility are attributes based on trust which, in contrast to other product properties, cannot be directly assessed by the consumer of interim or final products before or after the sale. This makes the quality of such a labelling system extremely important. It should be based on scientifically founded parameters and verifiable measurements. Furthermore, all relevant information should be at least available on request, if not already provided within the scope of the document and transparently clarified.

A representative EU-wide survey on the opinions of EU citizens on environmental properties of products, carried out by request of the EU commission, found that EU citizens tend to have more confidence in the environmental labelling issued by third parties (66% agreement) than in self statements of manufacturers who market their products as environmentally friendly (52% in Europe, only 31% in Germany) (European Commission and TNS 2013). According to a study of the German Federal Environmental Agency UBA (Grunenberg and Kuckartz 2013), the plausibility of environmental labelling rises when:

- the labelling is designed and issued by several partners jointly (e.g. "Blauer Engel")[41],
- the work of the participating parties is completely verifiable on a national or an international level
- the access to such verifiable information is guaranteed
- conflicts of interest (e.g. between potential recipients of labels and the assessors) are avoided (Delmas, Nairn-Birch & Balzarova 2013).

For potential users of environmental labelling, the related costs and the turnover are also of great relevance. Whether specific environmental labelling only causes additional costs or also leads to direct increases in turnover is not conclusively proven and can only be assessed using corresponding indications in assessment of public acceptance. For example, the previously mentioned study of the European Commission asks citizens to evaluate their confidence in environmentally friendly products and their importance. From the results, however, a complaisant attitude towards these products can be concluded, while concrete statements on their impact on actual decisions to buy cannot be concluded from these results (European Commission and TNS 2013).

7.3. Environmentally related messages of CCU products and processes

A possible label for CCU processes or for products manufactured under the implementation of CCU processes could make reference to various properties. From the basic potential of CCU products and processes described at the beginning (see Chapter 2.3.), four topical messages were derived (see Figure 8) on the basis of which a certification or product designation could possibly be built. These are:

- Reduced CO_2 footprint (see Chapter 2 and 4)
- Reduced consumption of fossil resources (see Chapter 2 and 4)

[41] In this case, there are four organisations:

1. The Jury Umweltzeichen (Environmental Labelling Jury) is the independent decision-making committee of the "Blauer Engel" with representatives from environment and consumer associations, unions, industry, trade, tradesmen's associations, communes, science, media, churches, youth, and the Federal German states.
2. The Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety is the issuing body of the labels and also issues regular information on decisions of the Jury Umweltzeichen (Environmental Labelling Jury).
3. The Federal Environmental Agency (UBA) works within the scope of "ecological design, environmental labelling, environmentally friendly procurement" as the "Blauer Engel" main office and develops the functional criteria of the bases for issue of the "Blauer Engel".
4. The RAL gGmbH is the issuing body for labels. Within the process of development of criteria, it organises the hearings of independent experts, i.e. the inclusion of interested circles.

   Cp. https://www.blauer-engel.de/de/der-blaue-engel/wer-steckt-dahinter, August 11, 2016.

- Product is relevant for (closed loop) recycling management and/or recycling [42] (see Chapter 2 and 6)

- Product contains CO_2 as a raw material (please refer to Chapter 2 and 4)

The combination of these properties and the previously described existing possibilities for certification led to a series of labelling scenarios (please see also table 7), which are more closely described in the following section.

Possible messages referring to CCU based products

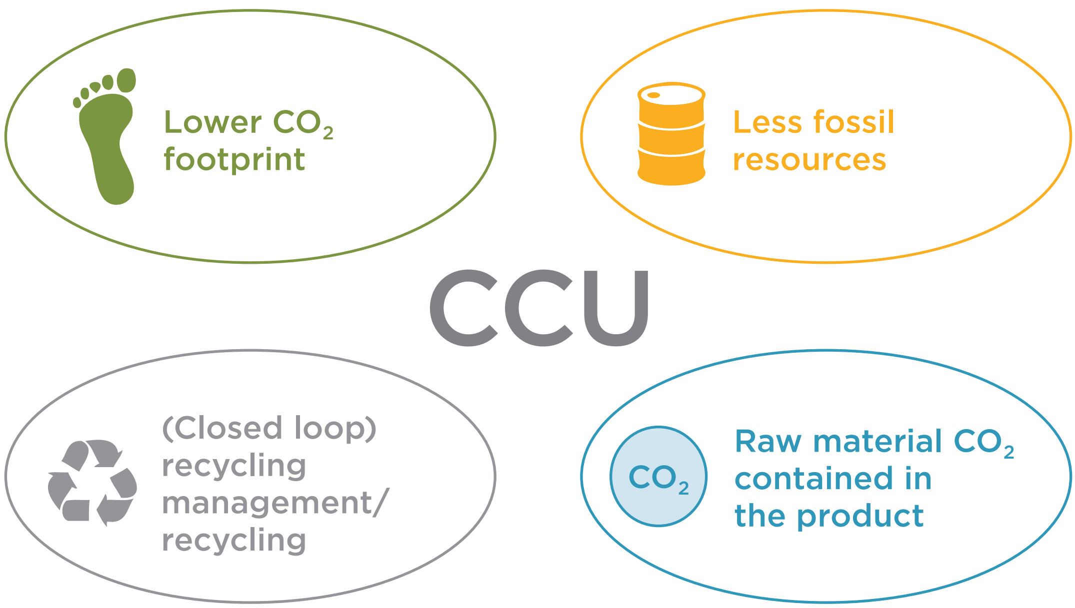


Figure 8: Possible messages of a product manufactured under the implementation of CCU technology which could be used as a basis for labelling or certification

Source: IASS

[42] (Closed loop) recycling management defines a concept of leading resources that are utilised in production as completely as possible (i.e. waste free), into further utilisation. Recycling processes are part of this concept, but are also supplemented by other forms of further use, such as cascade utilisation. In this text, both terms are used: (closed loop) recycling management stands for the conception of the objectives while recycling is a concrete process on the way to this. The European Guidelines for dealing with waste were determined in the German Life Cycle Resource Management Act (Kreislaufwirtschaftsgesetz (KrWG)) in 2012. cp. also: https://www.umweltbundesamt.de/daten/abfall-kreislaufwirtschaft#strap1, https://www.bmwi.de/DE/Themen/Industrie/Rohstoffe-und-Ressourcen/entsorgungs-und-kreislaufwirtschaft.html. Accessed 3/11/2016.

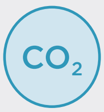
Message	Type of label / Type of product	Certified eco label type I (ISO 14024)	Certified eco label “type I like”	Self declaration type II (ISO 14021)	Environmental declaration type III (ISO 14025)
	Intermediate product (B2B communication)	Not possible, type I certificates always represent more than one property	Possible, not very useful since B2B customers are not the target group	Possible, to recommend as a declaration option for a strategic alliance of users	Possible and recommended as part of an environmental declaration
	End product (B2C communication)	Not possible, type I certificates always represent more than one property	Possible and recommended	Possible, to recommend as a declaration option for a strategic alliance of users	Possible, not very useful since final customers are not the target group
	Intermediate product (B2B communication)	Not possible, type I certificates always represent more than one property	Possible, not very useful since B2B customers are not the target group	Possible, to recommend as a declaration option for a strategic alliance of users	Possible and recommended as part of an environmental declaration
	End product (B2C communication)	Not possible, type I certificates always represent more than one property	Possible and recommended	Possible, to recommend as a declaration option for a strategic alliance of users	Possible, not very useful since final customers are not the target group
	Intermediate product (B2B communication)	Not possible, type I certificates always represent more than one property	Not possible, message displays product properties, not ecological effects	Possible, to recommend as a declaration option for a strategic alliance of users	Not possible, no information about ecological effects of the product
	End product (B2C communication)	Not possible, type I certificates always represent more than one property	Not possible, message displays product properties, not ecological effects	Possible, to recommend as a declaration option for a strategic alliance of users	Not possible, no information about ecological effects of the product
	Intermediate product (B2B communication)	Not possible, type I certificates always represent more than one property	Not possible, message displays product properties, not ecological effects	Possible, to recommend as a declaration option for a strategic alliance of users	Not possible, no information about ecological effects of the product
	End product (B2C communication)	Not possible, type I certificates always represent more than one property	Not possible, message displays product properties, not ecological effects	Possible, to recommend as a declaration option for a strategic alliance of users	Not possible, no information about ecological effects of the product

Table 7: Overview of potential certification scenarios for CCU products and processes

Source: IASS

7.4. Scenarios for the labelling of interim and end products manufactured under implementation of CCU technology

The messages in figure 8 that are related to CCU products and processes could be integrated in various ways into the framework of possible certification explained in Section 7.1. Several scenarios can be considered, which are presented in an overview in table 7. The differences in the objects to be labelled should also be taken into consideration – interim products, end products, product types, as well as an alignment to the final costumer, either B2C or B2B.

7.4.1. CCU message 1: Reduced CO_2 footprint

The potential message "reduced CO_2 footprint" is possible to mediate using numerous existing certification options. A reduced CO_2 footprint is considered a relevant form of environmental impact as regards climate change and is already taken into consideration, generally within the scope of life cycle impact assessment methods (please refer to Chapter 4.). For this reason, various labelling types can be pursued for CCU products.

According to the current stage of development, labelling of Type I is not an option for this message, due to the fact that a reduced CO_2 footprint only constitutes a single form of environmental impact, whereas an environmental label of Type I always contains several factors for a specific product or product type.

Feasible for the labelling of a reduced CO_2 footprint would be a "Type I-like" certificate, which only describes a single instance of environmental impact, for B2B and B2C communication, a Type II certificate (ISO 14021) for self-declaration, or an environmental declaration according to Type III (ISO 14025).

7.4.2. CCU message 2: less fossil resources

In addition, the reduced utilisation of fossil resources is included as an important message for the potential of CCU technology in the existing certification models, at least partly. Reduced consumption of raw materials usually applies as environmental impact due to the lack of fossil fuels and is already taken into consideration as an environmental category in the most frequently utilised life cycle impact assessment methods (please refer to Chapter 4.). Consequently, various labels can be pursued for CCU-based products.

Also, for the CO_2 footprint, a certification of "Type I" is currently not feasible for the use of resources, because only one aspect of environmental impact has been named. It would however be feasible to have a label in the form of the certified labelling "Type I-like" for B2B as well as for B2C communication, a Type-II certificate for self-declaration (ISO 14021) or within the scope of an environmental declaration according to Type III (ISO 14025).

7.4.3. CCU message 3: (Closed loop) recycling management/recycling

The message "Recycling/Closing cycles" can be integrated in existing certification systems, but is connected with substantial difficulties of definition in relation to CCU. Any form of labelling would have to overcome these difficulties, as described on page 76.

WASTE, RECYCLING, REUSE, RECOVERY: TERMINOLOGICAL HURDLES IN THE CONTEXT OF THE GERMAN LIFE-CYCLE RESOURCE MANAGEMENT ACT (KRWG)

One fundamental prerequisite for the labelling of a process as "recycling"[43] and a raw material or ingredient as "recycled" CO_2, would be the classification of CO_2 as "waste" according to valid legal regulations. At the moment, CO_2 is recognised as a greenhouse gas, but is not defined as waste: according to the **KrWG** (see § 2 Scope of Validity), only gaseous materials which are stored in containers are to be treated as waste. According to this principle, CO_2 emissions from industry would not be classified as "gaseous waste", because CO_2 compaction and storage in containers is not a fundamental prerequisite for CCU.

Problematic within this context of definition, in addition, would be the fact that the option of utilising CO_2 from the atmosphere (please also refer to Chapters 2.2. and 5.2.1.) could not be taken into consideration in the scope of such a model of certification. This is due to the fact that the carbon dioxide contained in the atmosphere is recovered and recycled through biological or chemical-technical procedures. CO_2 recovered in this way is, consequently, not by definition "waste", i.e. rest products which occur during preparation, manufacture, or utilisation of something else, thus, a possible basic material of a declared recycling process.

At best, the process could be defined as **re-use**[44]. But this label would also not be precise, due to the fact that the term "re-use" in the KrWG refers to constituent parts which are not waste and are used a second time for their original purpose. At least for CO_2 emitted from industrial plants, this is not the case.

According to the definitions of waste hierarchy, CO_2 **"recovery"** would be a more fitting term: "Recovery" in the sense of the KrWG Section 3, Art. 23 (Bundesgesetzblatt 2012) is "any procedure which has as its main result the forwarding of waste within the plant or within the further economy to another

[43] In contrast to the term "reuse" stands "recycling", in the sense of the "KrWG" any procedure for reuse of the waste of products, materials or substances, either for the original purpose or for other purposes; this includes the treatment of organic materials, not however, the energetic recovery and treatment of materials which are to be used as fuels or filling materials"; (Bundesgesetzblatt 2012)

[44] "Reuse" in the sense of the KrWG is "any procedure during which products or constituent parts which are not waste are used once again for the same purpose, for which they were originally intended"; KrWG Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschaftung von Abfällen (Kreislaufwirtschaftsgesetz). (Bundesgesetzblatt 2012)

sensible purpose, either to replace other materials which would otherwise be used to fulfil a specific function or to prepare the waste in such a way that it fulfils this function."

Although for CCU processes, only the term "recovery" can be used in the waste treatment hierarchy, in practice, labels from the area of recycling must be observed, due to the fact that the category "recovery" contains no separate label for the B2C area.

In the area of recycling, there is a large inventory of labels which are generally based on the Universal Recycling Symbol. These symbols were developed in order to simplify the recycling procedures in waste management and to communicate a multitude of aspects of information, ranging from the classification of materials, which was intended to simplify disposal of products, to the contents of recycling materials.[45]

Although processes which use emitted CO_2 can, conceptually, be regarded as recycling processes, the available variation of the Universal Recycling Symbol makes the communication of such a product as a CO_2-based product probably the most difficult example to implement. In one respect, if the percentage value of the CO_2 content has to be named, the proportion of recycled material within the end product can be too low for the product to qualify for the corresponding certification. However, in contrast, the recycling symbol primarily refers to the ability to recycle the product itself or to a specific ingredient which can be recycled or which is of importance with a view to product disposal, however, not to a recycled material contained within the chemical composition of the materials. Furthermore, such a symbol is not to be employed for the usage of CO_2 in the production of energy sources, due to the fact that it exclusively describes processes of utilisation as materials.

The certification scenarios in table 7 make it clear how limited the options are to allow this aspect of CCU products to be considered within the framework of certification – neither a designation according to Type I nor "Type 1-like" is possible according to current developments. Only a self-declaration according to Type II can be pursued.

Furthermore, the possible message of recycling and (closed-loop) recycling management only serves to emphasise the fact that CO_2 was reused or recycled, but it does not describe how the CO_2 remaining in subsequent utilisation affects the environment (e.g. due to the duration of binding or increased efficiency; please also refer to Chapter 2.3.), because these effects differ extremely depending on the specific CCU application. For this reason, an integration of the recycling aspect in the designation of Type III is also not possible to implement.

[45] For example: https://www.scsglobalservices.com/recycled-content-certification, http://www.recycle-steel.org/~/media/Files/SRI/Media%20Center/LEED_Oct2012.pdf, http://www.savoia.com/news.php?s=news&n=50&lang=en. Accessed 3/11/2016.

The Icelandic company Carbon Recycling International already uses a carbon recycling logo which takes direct reference to the Universal Recycling Symbol:

Figure 9: Logo page of the company Carbon Recycling International

Source: Website of Carbon Recycling International, http://carbon-recycling.is/, June 2016

There is also a variation on the Universal Recycling Symbol to be found on the internet for CO_2, however, without an identifiable originator.

Figure 10: CO_2 related version of the Universal Recycling Symbol.

Source: http://stoppingclimatechange.com/sitemap.htm und http://www.wabisabinews.com/#!Recycling-CO2-%E2%80%93-with-Diamonds/cjds/56feaa7b0cf21ff2b5fcd528/, both June 2016

7.4.4. CCU message 4: Raw material CO_2 contained in the product

For the message "Raw material CO_2 contained in the product" a specific label in accordance with Type II (self-declaration) would be suitable for CCU products. Such a label would be applicable to a great bandwidth of products of CCU processes, under the condition that the companies and associations concerned can come to an agreement on common criteria for the issueing of a corresponding label. The value of such a label depends, on the other hand, on transparency and understanding as criteria during the development phase.

One advantage and one disadvantage lie in the large variation in the products which are to be labelled, due to the difficulties in finding measurement parameters which would lead to ease of comparison.

Due to the fact that the CO_2 contained in the end product, i.e., after conclusion of the production process, has no effect on the environment, the property is not to be considered as directly related to the environment. Designation of labels of categories Type I and Type III would for this reason not be feasible.

A hazard of such self-developed labels is the potential misunderstandings that could result in light of the fact that CO_2 utilised in a product does not necessarily mean that the product itself has better properties for the environment. This could be avoided, for example, if only products with a positive life cycle assessment were labelled/certified, which, however, would lead to extremely strict controls through the issuing body of the certificates.

7.5. Labelling options

7.5.1. Options for labelling of CO_2-based products for B2B customers

For the communication with business customers (B2B), environmental declarations of Type III are recommended for CCU interim products. Labels of this type include comprehensive environmentally relevant information and do not evaluate in any specific direction, due to the fact that they abstain from weighing up the specific properties. Consequently, a reliable, transparent and simultaneously flexible application of individual labelling for possible subsequent products remains possible, allowing the recipient to personally decide which environmental aspects are the most important ones for the respective product communication.

7.5.2. Options for labelling CO_2-based products for the final consumer

Consideration of these scenarios makes it clear that there are, in principle, a number of possibilities for labelling CO_2-based products using existing systems. In the sense of higher plausibility and familiarity, with regards to the consumer as well as standardised procedural methods in the labelling process, integration in the existing designations, ideally in Type I certifications for the final consumer, would be an appropriate goal. There are, however, diverse obstacles which would prevent labelling of this kind.

Designation of CCU-based final products would have to be product specific and, consequently, would be difficult to transfer to various product types; for this reason it cannot be generalised to the entire bandwidth of CCU options.

The necessary creation of transfer options for quantifiable effects on the environment, in the case of these extremely heterogeneous products is, therefore, not feasible or only to a very limited degree for CCU products, so that certification and labelling according to Type I, such as in the case of the "Blauer Engel" for recycling paper, are not possible to implement. On the other hand, it would be conceivable to integrate the utilisation of an efficient CCU process in the manufacture of a product, as *one* evaluation criterion within the life cycle evaluation process for Type I certificates, insofar as this occurs transparently and in accordance with the standards described in chapter 4.

In all cases, a certification of CCU products would, however, require an adaptation or expansion of the existing evaluation categories – this would make a realisation of plans possible in the mid-term at the earliest. An assessment of this kind could then be integrated in the product categories for which a Type I label already exists.

A further obstacle for the creation of a Type I certification for CCU products would be the relatively high associated costs, not to mention the influential third-party control of the certification process.

This situation is, however, completely different if the possibility of a certification according to Type II or Type III is considered. Here, the responsibility for the development lies with companies and/or the relevant associations, in particular with regard to the selection of the individual environmental aspects to be emphasised (Type II) and the process of working out and agreeing on common Product Category Rules (PCR) (Type III).

A Type II label is consequently possible to implement immediately; however, this would, from an environmental perspective, only be convincing and directly verifiable with a view to messages 1 and 2. A Type III label can be used under the condition of successful development of the PCR for CCU processes and products, as previously described, which also seems possible to implement in the short term on the basis of scientific development, which is already in advanced stages, and the high quality of available literature on LCAs in CCU processes and products (please also refer to Chapter 3.2.).

Overall, certifications of Types II and III in the early stages of development of many CCU technologies, up to the point of the achievement of a wide marketability, seem to be the only direct and simultaneously relatively autonomous possibility (for companies) to implement product labelling.

Certifications of Type II provide a less complex form of assessment than the known certifications of

Type I, while certifications of Type III do not, however, offer assessments, but only values. It can nevertheless be assumed that a transparent and understandable self-declaration developed for the CCU sector – which, of course, includes all the necessary properties of Type III declarations, such as being in accordance with DIN EN ISO 14025, addressing the necessary PCR – should be classified, up to a certain point, as functional (for messages 1 and 2) and as necessary (for messages 3 and 4).

Preconditions for certification of more than one individual CCU product with a designation of Type II would be the early formation of an alliance of users of CCU technologies or, in the case of interim products, their recipients – if feasible already in the development phase – as well as strict compliance with the principles of DIN EN ISO 14020 and concurrence with the German Act against "Unfair Competition" (UWG), in order to guarantee plausibility and verifiability.

A further conceivable option for designation of CCU products, with regards to the final consumer, would be a label which is outside of the existing certification system and the relevant ISO standards. Such a label for use by producers of possible CCU products in the industry would have the advantage of offering a simple message to final consumers in a quick and less complicated fashion. The development of such a label could, as a prior step, be integrated in the development process of other certification options. Such labels are, however, not an option for environmental aspects or effects on the environment. If the information offered by them is unclear or not externally verifiable, they fall under the suspicion of making a product seem possibly more environmentally friendly than it actually is.

7.6. Conclusion

Generally, possible labelling of CCU products is associated with various advantages and disadvantages:

PROs	CONs
■ Increase in the familiarity of CCU processes in the B2B and in the B2C sector	■ Extremely limited possibilities of application for end products within the existing certification landscape; therefore, possible to implement as Type I and/or integrated in Type I – only possible to implement in the mid to long-term
■ Increase in the motivation to buy CCU-based products in B2B and B2C sectors	■ In the case of final products, the question of visibility arises due to the multitude of available labels
■ A relatively short-term introduction period for B2B communication seems feasible (Type III)	■ High effort and high costs of certification (in particular for Type I and Type III)
■ Relatively short-term introduction period as Type II for end products seems feasible	■ In the case of CCU products, possible direct effects of labels on turnover can only be planned with great difficulty
■ Announcement in society of technology which offers alternatives to the consumption of fossil resources	

Table 8: Pro and contra CCU labelling

Source: IASS

Even if there are currently still a great many uncertainties in the perspectives regarding labelling and several obstacles to be overcome in the further design and achievement of a certification for CCU products, it is still recommended to parties in industry and associations to begin to consider and perhaps prepare designation and certification options in cooperation with experts from the fields of environmental protection and certification.

Working out joint interests on the way to a certification, as well as individual assessment of the options named by industry, associations and relevant areas of science, are unavoidable for the further development of the possibility of transparent labelling of CCU products. Within the scope of the perhaps necessary process of working out PCR for the CCU field, the current status of scientific works available on the topic of LCA must be taken into consideration in order to find sensible compromises to solving critical aspects in the methods, for example, in the form of selection of allocation criteria (please also refer to Chapter 4.). Ease of understanding must be guaranteed for certificate options for final consumers. In addition, the international applicability of possible options should be assessed and taken into consideration.

In addition, the question of the acceptance to be expected in the producing and processing industries remains open, as well as the willingness of the consumer to appreciate products with such labels and to buy them.

"Can CO_2 be recycled? A dialogue on Carbon Capture and Utilization (CCU)" on June 5th, 2014, at the IASS Potsdam. Here: Philipp Sommer, Deutsche Umwelthilfe, Florian Teipel, econsense, Carsten Dreher, FU Berlin. © IASS/Christian Kruppa

8. Differentiating CO_2 from CCS

CCU is often confused or categorised together with CCS (Carbon Capture and Storage), not least due to the extremely similar naming terminology and abbreviation (Oettinger 2011, McConnell 2012, Smit et al. 2014). Despite some technological overlaps, the two concepts have considerable points of difference, so that confusing CCU with CCS is problematic for many reasons. This confusion can even cause obstacles for the further development of CCU. In the following, the differences between the two concepts shall be made clear and recommendations will be derived on how these differences require specific treatment on the part of policy.

8.1. Carbon Capture and Storage (CCS)

The concept of CCS has been discussed as a central method of reducing anthropogenic CO_2 emissions from large point sources such as coal-fired power plants (Haszeldine and Scott 2011, Scott et al. 2013, Scott et al. 2015). According to the IPCC mitigation scenarios for the achievement of the international climate goals (RCP 2.6), CCS shall contribute a total of approximately 25% of the entire emission reductions from fossil power plants and other plants operated with biomass (BECCS) up to the year 2100 (IPCC 2014). With this in mind, CCS has received a great deal of attention from politicians and other stakeholders such as the International Energy Agency (IEA). Although CCS is an accepted mitigation measure in the European emissions trading and in Clean Development Mechanism, it has not been possible to develop an economically suitable concept for CCS, not least due to the high costs for capture and storage and the CO_2 price which has been low up to now (Haszeldine 2009).

In some countries, including Germany, the general public has a very critical attitude to the concept of CCS (Brunsting et al. 2011, de Coninck and Benson 2014, Selma et al. 2014) which is often seen as an attempt to delay the decarbonisation of the fossil industry. In particular, the argument of "clean coal" is often seen as an argument against the abandonment of the coal-based power generation (Stephens 2014). While the development and implementation of CCS is progressing in slow steps and is subject to setbacks (Bloomberg 2013, TheLocal 2014, BBC 2015), the concept remains on the political agenda in the EU and many countries (GCCSI 2013, IPCC 2014, European Commission 2016, US DOE and NETL 2016).

8.2. Commonalities and differences between CCU and CCS

The central intention of CCS is the "permanent" removal of CO_2 (> 1.000 years) (Metz et al. 2005). The most important functional difference in this context between CCU and CCS is, therefore, that most CCU technologies do not allow for long-term storage of CO_2. After a particular period of time, the used CO_2 will be emitted again. Depending on the lifetime of the respective CCU product, the CO_2 can be stored for days or weeks (e.g. synthetic fuels), years (e.g. polymers) or decades or centuries (e.g. cement) (Styring et al. 2011, von der Assen et al. 2013) (please also refer to Chapter 2).

Also with regard to the total amounts of CO_2, CCU and CCS differ considerably. Even extremely optimistic estimations assume that only comparatively small quantities of CO_2 can be used (around 180 Mt (~ 0.5% of the anthropogenic emissions) for the manufacture of chemicals, and 2 Gt (~ 5.5%) for the manufacture of fuels (Ausfelder and Bazzanella 2008). Particularly in comparison to the CCS targets – e.g. of the IEA for the year 2050 of 7 Gt annually saved CO_2 – the potential of CCU seems to be quite small (IEA 2013). In addition, among the various CCU approaches, the greatest potential for usage is seen in technologies that only allow for very short storage duration (CO_2-based fuels). Furthermore, it must be considered that the evaluation for usable CO_2 emissions are not to be considered equal with reduced CO_2 emissions, since all conversion technologies also require energy. For each individual CO_2 utilisation technology, it is therefore necessary to determine the potential for CO_2 reduction individually – this can be higher or lower than the amount of CO_2 which can be used.

At the moment, CCU technologies are therefore not of great strategic relevance to climate protection. In particular, they cannot be used as an argument for extending the lifetime of fossil power stations because they would probably not, or only under very specific conditions, provide beneficial climatic effects that could outweigh the damaging climatic effects of power plants.

For a more detailed analysis of the commonalities and differences between the two concepts, we refer to the corresponding publication of the authors in the magazine Environmental Science & Policy (Bruhn, Naims & Olfe-Kräutlein 2016).

8.3. Problems resulting from confusion of CCU and CCS

Currently, it can be observed that CCU and CCS are being confused with each other in the most diverse political contexts (AIChE 2016, ISIGE 2016, University of Sheffield 2016) or that CCU is being seen as a sub-category of CCS, for example by the U.S. Department of Energy (US DOE and NETL 2016) as well as instances in comprehensive scientific reports (Metz et al. 2005, McNutt et al. 2015).

CCU is also increasingly discussed within the context of climate protection and, in this context, is treated together with, or in comparison to, CCS (Metz et al. 2005, Raab 2014, McNutt et al. 2015). For example, Poland hopes that CCU will help the country to achieve its own climate protection targets without reducing the use of coal too quickly (Getzner et al. 2005, Adamczewski 2015).

One of the consequences of this confusion is that numerous parties primarily view and consider CCU with respect to its possible contribution to the (inter-)national climate protection goals (Markewitz et al. 2012, Hendriks et al. 2013, Oei et al. 2014). CCU is often defined as the *alternative* to CCS, pursuing the goal of using CO_2 (closing the carbon cycle) instead of storing it (Armstrong and Styring 2015, Kilisek 2015). As a result of such argumentation, some, particularly in Germany, have expressed scepticism or rejected CCU due to its limited climate protection potential (Lasch 2014). With this in mind, it is often not considered that substantial positive effects of CCU technology are not directly associated with climate protection (von der Assen et al. 2013, Bennett et al. 2014). Further confusion of CCU and CCS would reinforce the impression that CCU should be particularly observed from a climate protection perspective. This leads to the other possible potential advantages of CCU being overlooked.

Again problematic is that CCU is often seen as a means of promoting the implementation of CCS (Mikkelsen et al. 2010, Styring et al. 2011, Zero Emissions Plattform 2013, Ericson et al. 2015). In addition, it is also often stated that CCU can contribute in early phases of CCS to improve its profitability (Zero Emissions Plattform 2013, Santos 2015). The use of such argumentation for CCU can promote the perception that CCU and CCS pursue common strategic goals and possess comparable potential. As we observed during our stakeholder dialogues (please also refer to Chapter 6.1), parties who are sceptical towards CCS tend to transfer this attitude directly to CCU (Naims et al. 2015, IASS 2016). In particular, the intentional commingling in the form of CCUS as, for example, used by representatives of the fossil energy economy, and widespread in the USA, serves to foster the impression that CCU is only a further strategy serving to extend the operating life of fossil energy production, hindering a decarbonisation of industry (Zero Emissions Plattform 2013, Ericson et al. 2015, ICO2N 2015). As a result of such impressions, CCU, for example, has also been called the "Fig leaf for CCS" (Lasch 2014).

In summary, it can be seen that the dynamics which result from the confusion of CCU and CCS are not conducive for the formation of unbiased assessments of CCU (please also refer to Chapter 6.3.). In addition, such confusion could serve to reduce public and political support for CCU and negatively affect the further development and implementation of CCU.

8.4. Political relevance of distinguishing between CCU and CCS

The differences between CCU and CCS described here, as well as the problems which result from their confusion, suggest that both concepts have to be adequately distinguished in the scope of the current political debate. In order to support the development of well-informed public opinion and corresponding political instruments of support, the specification of both concepts must be done justice, in particular in regard to the following fields of environmental policy:

Climate protection: In contrast to CCS, CCU should not be treated foremost within the scope of climate protection. To reduce CCU to a climate-protection measure means to overlook important aspects of the original motivation and possible potential of the concept. Moreover, the potential of CCU to contribute to negative emissions should, for this reason, not be overemphasised. In any case, the time limitations in duration of CO_2 storage and differences for individual CCU applications must be adequately explained. Moreover, the possible indirect effects on the climate through substitution of other resources and possible energy-efficiency wins should be considered in individual cases. Confusion of CCS and CCU in regard to the abbreviation CCUS serves to undermine clarity and supports the misunderstandings described above. In order to avoid possible disappointments, research on CCU should, in particular, not be treated as support for CCS, as is currently the case in diverse institutions worldwide (Oettinger 2011, McConnell 2012).

Energy transformation: CCS was suggested as a strategy to reduce the climate damaging side-effects of fossil energy production and includes a total increase in costs for energy production (IEA 2013). The concept constitutes no contribution to the transformation of energy systems with regard to moving away from fossil infrastructure. CCU technology, in contrast, could contribute to the replacement of fossil resources and, in so doing, provide support for transformation of energy systems to renewable sources, in particular also in sectors outside of the energy industry, such as production and in the transport sector (Klankermayer and Leitner 2015).

Securing raw materials: While CCS supports existing raw material strategies, CCU technology offers the possibility for the improved management of raw materials and recycling, as pursued through the vision of (closed loop) recycling management (Bringezu 2014, World Economic Forum 2014). CCU technologies should therefore be integrated in political strategies for securing raw materials and resource efficiency.

8.5. Conclusion

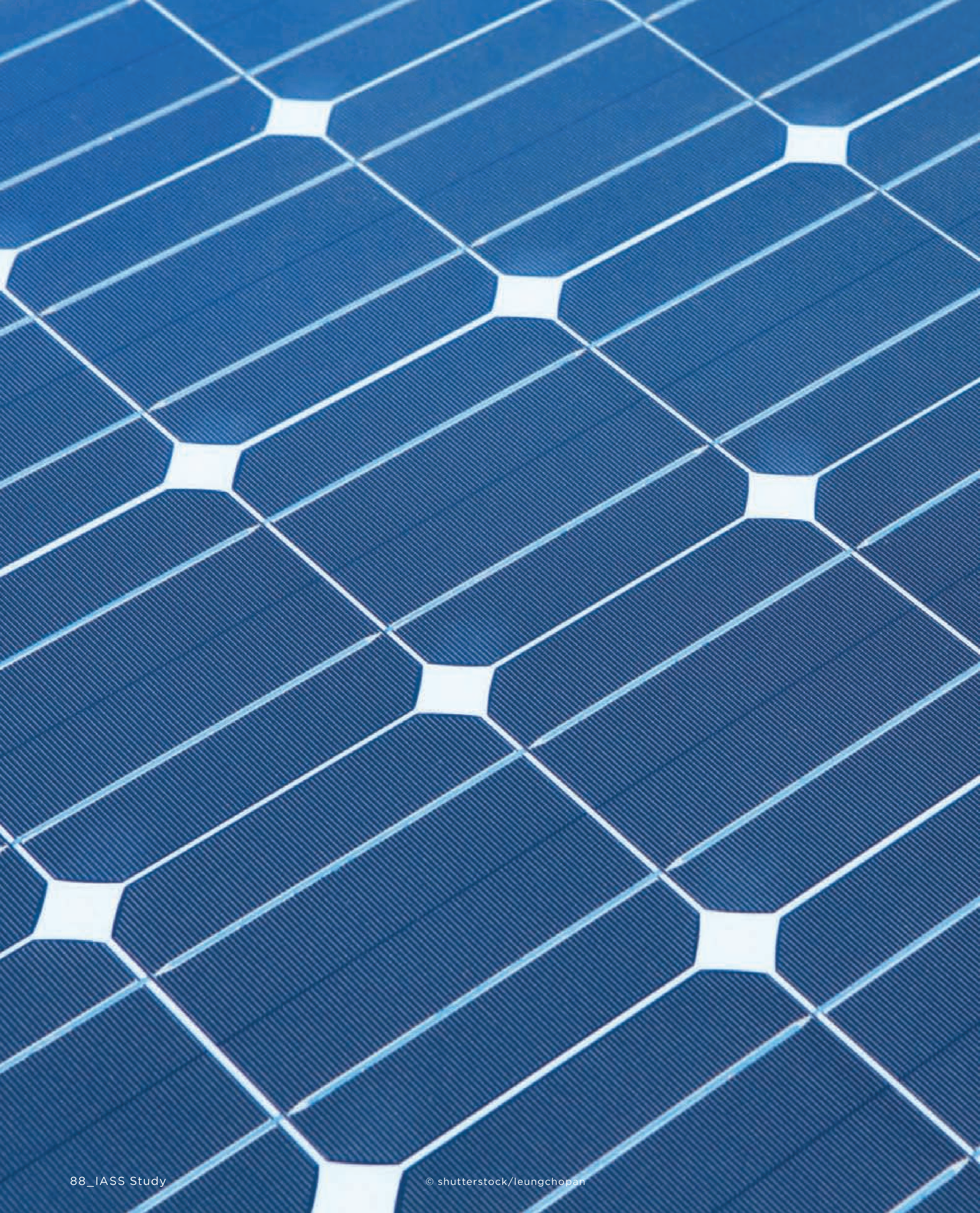
An important result of the confusion of CCU and CCS is that CCU is, in particular, evaluated in regard to its climate protection potential. This perspective cannot do justice to the various important areas of potential of CCU and, partly, can even lead to CCU not receiving the public and political support which it requires for further development. This is particularly the case in Germany, given that the general public is extremely sceptical and dismissive towards CCS. Confusion of CCS and CCU should therefore be avoided in public discourse.

In addition, CCU should be increasingly embedded in topic areas related to securing raw materials and energy transformation. It may well be appropriate, in this regard, to speak of CO_2 recycling or CO_2 utilisation, rather than CCU, in order to avoid the semantic proximity to CCS. How such definitions correspond, for example, with the relevant legal-definition parameters and conditions, such as those of the KrWG in the area of recycling, must be thoroughly clarified (please also refer to Chapter 7.).

In order to allow for a transparent and appropriate discussion on the potential climate protection effects of CCU, it is imperative to take into consideration that CO_2 is only temporarily stored in CCU applications, thus emissions are only delayed, although increases in efficiency within the context of CCU development and implementation can, in individual cases, lead to important emission reductions. The development of instruments, for example, on the basis of technologically specific LCAs, which make such assessment and comparison with other climate protection measures possible, is a central challenge for the future.

“Can CO_2 be recycled? A dialogue on Carbon Capture and Utilization (CCU)” on June 5th, 2014, at the IASS Potsdam. Here: Alberto Varone, IASS, Wolfgang Schmid, Audi, and Sebastian Becker, sunfire (from left to right).

“CO_2 recycling – option for politics and society? A dialogue on Carbon Capture and Utilisation (CCU) technologies” on November 9th, 2015, at IASS in Potsdam. Chair: Jens Schröder, GEO.



9. CCU in the context of the energy transition

Possibilities, perspectives and limits of various aspects of CCU were discussed within the topic-specific sections of this report. In order to take all aspects of the societal relevance of CCU into consideration, possible connections with other societal processes must also be reflected. In particular, questions related to the energy transition are relevant for the assessment of CCU technology.

Part of the work of the project at the IASS was, for this reason, to cast light, from various perspectives, on possible interfaces of CCU to important questions related to the energy transition towards renewables. This occurred within the scope of internal workshops at the IASS as well as through discourse within the scope of the Round Table events (please also refer to Chapter 6.1.). In summary, two particularly important questions could be identified which should play a role for consideration of CCU within the scope of the transformation of energy systems to renewable energy:

1. Where is the CO_2 that is to be used supposed to come from, and do these possible sources conflict with the goals of the energy transition?

2. To what degree can CCU technology for energy storage supplement the energy transition in a sensible fashion?

Both questions are taken into consideration in the following summary.

9.1. CO_2 sources and possible conflicts with the energy transition

A central goal of the energy transition is to avoid a substantial part of the CO_2 emissions – i.e. those resulting from fossil energy production. In particular, the mid to long-term abandonment of fossil energy production in Germany is in discussion.

A concern expressed over and over again is, for this reason, that a comprehensive implementation of CCU technology could, in the long term, lead to an increase in demand, i.e. an actual "requirement" for CO_2 from emissions. This would lead to **path dependencies** which would render the abandonment of fossil power plants difficult or even hinder such efforts.

This could, for example, be the case if new plants are built which capture CO_2 from coal-fired power plants for reuse. The discontinued use of these coal-fired power plants would, thus, make conditions for CCU applications difficult.

A closer consideration of the possible supply and demand sides of CO_2 (please also refer to Chapter 5.) shows, however, that within the foreseeable future, the CO_2 emissions from highly concentrated industrial **CO_2 sources** are sufficient to cover the demands for CO_2 for CCU purposes.

Again in the long-term, extensive CO_2 demand could be covered by emissions from various sectors such as the cement and steel industry without dependency on energy production (Naims 2016). Further sponsorship and comprehensive implementation of CCU technology is therefore not dependent on emissions from fossil driven power plants.

Furthermore, the capture of CO_2 at plants for preservation of the basic load of an energy system based on renewable energies (e.g. biogas plants or PtG-/PtL plants) is not only conceivable, but has already been tried out in individual cases (see Audi's plant in Werlte, which uses CO_2 from a biogas plant) (Eckl-Dorna 2013, Strohbach 2013).

In the long term, there is also the possibility of the capture of **CO_2 from the air**. However, in order for these technologies, which are still in an early stage of development, to make a contribution to climate protection, the necessary energy for capture and compressing of CO_2 would have to come from renewable sources (Brandani 2012).

- **In the case of the suitable implementation of CCU technology, path dependencies with fossil energy production can be avoided.**

9.2. Energy storage with CCU to supplement the energy transition

Due to the fact that CO_2 contains very little energy, the transformation of the molecule into products of higher value generally requires energy. In order for this transformation to result in a positive environmental performance, the availability of renewable energy is necessary for many of these technologies. In particular, for the implementation of environmentally related technology for the production of diverse energy sources on the basis of CO_2 and hydrogen, the latter must always be produced with the aid of renewable energy, in order to fulfil the claim of an improved life cycle assessment. Otherwise, direct utilisation of the fossil fuel energy would be more sensible.

These kinds of procedure are called Power-to-X (PtX); the X is a placeholder for G such as gas, L like liquids or C as in chemicals. On the basis of renewable energy and CO_2, a wide spectrum of carbon-based products and fuels can be manufactured which could play a significant role in the future. Sensible concepts of CCU on the basis of renewable energy are described in numerous articles on chemical products (Klankermayer and Leitner 2015), the mobility sector (Varone and Ferrari 2015), and specifically on the aerospace industry (Falter et al. 2016) and evaluated from an ecological perspective (Sternberg and Bardow 2015). PtX technologies are, therefore, an option for how the fluctuating offers for renewable energies can be utilised in a sensible way. At the moment they are still competing with other options of energy storage and flexible utilisation, as well as the export of electricity from renewable sources.

From an economic perspective, this kind of technology is generally not competitive due to the relatively low prices of fossil resources.[46] Currently, the proportion of renewable energy in the grid is so low (in Germany around 30%), that further capacities are generally used in the electricity market for reasons of efficiency. In a future in which considerably higher prices for fossil energy would dominate and/or a wide range of possibilities for cheap renewable energy were available, profitability of PtX would be feasible. For this reason, the ambitious climate protection vision of the UBA for a greenhouse-gas neutral Germany plans a significant proportion of PtX technologies (UBA 2014a).

[46] The company CRI in Iceland can produce competitively on the basis of the available geothermal energy. In Germany, the company Audi has introduced a fuel card system which forwards the additional costs of the climate neutral fuels directly to the consumer.

For the development and implementation of such CCU technologies that have to be combined with renewable energy, location-specific planning is necessary in individual cases, in order to ensure that renewable energy and CO_2 are locally available; here, the latter must in particular avoid the path dependencies described above. First analyses, however, reveal that these prerequisites are available in numerous locations in Germany (Mennicken 2015).

- **The widespread and cheap availability of renewable energy would support the further development and implementation of CCU technology. However, CCU technologies could contribute, through energy storage, to the achievement of the goals of the energy transition. Here, the technological options must be thought out in a portfolio which makes sense politically, ecologically and economically.**

This illustration is a "Graphic Recording" of the dialogue event "Can CO_2 be recycled? A dialogue on Carbon Capture and Utilisation (CCU) Technologies" held on June 5th 2014 at IASS Potsdam. The drawing contains different patterns of argumentation and questions that shaped the discussion. See also chapter 6.

10. Conclusions and recommendations for decision makers and disseminators in politics, economy and society

On the basis of the interdisciplinary work introduced in individual sections of this report, conclusions and recommendations for further treatment and development of CCU technology can be derived, which will be summarised in the following.

10.1. Environmental policy potential/ alignment of CCU

CCU technologies can make a contribution to (closed loop) recycling management and to securement of the resource base. Already, numerous applications are technically possible to implement while many others are in the early stages of development. These try to integrate the CO_2 which is emitted as a result of human activity as raw material again for production processes. A contribution to climate protection is feasible here, but should not be overestimated (Bruhn et al. 2016).

Within the scope of energy transition policies, CCU technology, through its potential uses, could potentially provide technical supplements in areas of energy storage. "Path dependencies" to maintain the fossil energy generation structure can be avoided if emissions which result outside the energy sector are used (please refer to Chapter 9.). Here, CCU and CCS can be clearly distinguished from each other (please refer to Chapter 8.).

In order for CCU technology to reveal its full potential within the scope of (closed loop) recycling management and the exploitation of alternative carbon sources, the support of political decision makers is necessary for technological development but also for the design of relevant legal parameters and conditions.

Conclusions and recommendations for eco-political discourse:

- Despite technical commonalities in the capture step, CCU and CCS concepts should be examined and evaluated separately from each other in research sponsorship.

- CCU concepts can provide supplementary input to the energy transition policies and should be planned on a complementary basis.

- To achieve important climate protection goals, CCU technology only has the potential to contribute a little; however, it can make a contribution in cooperation with energy transition policies and with other efficiency and mitigation technologies.

- CCU should not continue to be calculated into climate-political measures such as emission trading except in cases in which durable storage is proven (e.g. in building materials) as a direct emission reduction. Indirect calculation should be feasible with the existing emission reports and must still be clarified in detail for the concrete cases of individual plants and production chains.

10.2. Risks through carbon capture technologies of CO_2 from flue gases

As regards large-scale use of CCU technology, for example, the capture of entire CO_2 emissions of large fossil power stations, as is planned in some CCS concepts, and the capture of CO_2 from flue gases using amine scrubbing, can currently not be classified as being without cause for concern.

However, as described in Chapters 2. and 3., the total amounts of CO_2 which have to be captured for CCU concepts are considerably smaller than the quantities for which CCS could potentially dispose. It is probably feasible to cover short- to mid-term needs for CO_2 in CCU applications from more highly concentrated sources for which the utilisation of amine scrubbing is not necessary. The demand for CO_2 for CCU can also potentially be covered with the aid of carbon capture technologies which do not involve the risks of amine scrubbing described here. For the capture of comparably smaller quantities of CO_2, such as will be necessary in the foreseeable future for CCU applications, there are no considerations of significance to environmental or health risks (please see also Chapter 3.1.).

Wherever feasible, higher concentrations of CO_2 sources, which do not require the use of wet chemical absorption processes, should be used for the supply. Quantifying the effects on the environment of various scales of possible deployment of amine scrubbing remains an **essential task for current research** on this topic.

Conclusions and recommendations for carbon capture technologies:

- Further funding of basic research on efficient CO_2 capture and its further development is necessary.

- Possible "path dependencies" and lock-in effects for fossil energy infrastructure should be taken into consideration in future research funding.

- Future developments in the field of amine-based procedures for CO_2 capture shall serve to avoid the release of degradation products or components of utilised amines into the environment, particularly the atmosphere.

10.3. Life Cycle Assessment (LCA)

It cannot generally be considered as having been ascertained that CCU technology contributes to a reduction of CO_2 emissions in the atmosphere. Possible environmental effects of potential utilisation options of CO_2 must also be individually considered from case to case. To this end, an LCA methodology that can observe the entire life-cycle of a product is the suitable method; after all, a product can have an effect on the environment in any and all phases of its life cycle.

LCA methodology is already at a very advanced stage. Implementation on CCU technology with comparable, valid results, however, requires further research and efforts in industrial practice.

Conclusions and recommendations for the further development of Life Cycle Assessment (LCA) for CCU technology:

- In addition to the CCU core process and the upstream processes, it is also necessary to include the **downstream processes** in the LCA

  - if a new CCU interim product does not have the same chemical composition as the conventional product that it substitutes, it could, as a result, cause a change in the product properties, the operating life or the disposal requirements;

- if the aim is to produce **absolute rather than relative statements on a CCU product or on CCU technologies as fields of research.** In these cases, the total footprint of the product must be calculated, thus, a "cradle to grave" analysis is necessary.

- In order to guarantee ease of comparison of LCA results (please refer to Chapter 4.), LCA practitioners should enforce the **same conditions** for analyses.

- **Specific regulations** for the implementation of CCU related life cycle assessments under the same conditions should be determined by an expert team.

- As a consequence, as regards reliable communication (please also refer to Chapters 4. and 7.) general concurrence with the community in research and industry working on CCU technology, which also decides on **methods of determination and presentation of evaluation results**, would be necessary. The demands of ISO 14025 should provide a basis in this regard.

- Even if future CO_2 utilisation technologies could source all of the energy they required from renewable sources, possible effects on the environment should still be evaluated with the aid of LCAs, primarily in order to be able to pinpoint **improvement options as regards process efficiency**.

10.4. Economy

No general statements can be made on the profitability of CCU technology because it is determined by the specific technology and depends on a number of factors. Large-scale deployment of CCU technology could be advantageous from an economic perspective in the long term, as long as the proper parameters and conditions are created and technological breakthroughs are achieved. It is therefore recommended, within the scope of the promotion of further development and implementation of CCU to heed the following points:

Conclusions and recommendations on economic aspects of CCU technology:

- The further promotion of research and development on **CCU technology makes sense from an economic perspective** and can accelerate the accomplishment of various interesting innovations.

- Some CCU-based products, in particular fuels, are currently **not yet competitive** in comparison to cheaper energy from fossil sources. As soon as ecological benefit is foreseeable, incentives should be created to support the implementation of these technologies in specific sensible areas of utilisation.

- CCU can, in comparison to and in combination with other environmental technologies, have various **positive economic effects**, for example, synergy effects in production and a reduction of dependency on the import of fossil resources. The potential to benefit society as a whole should be taken into consideration and evaluated within the decision-making processes and in the further promotion of the technologies.

10.5. Communication

The success of technical innovations is also influenced by acceptance through the general public and consumers, in addition to aspects of feasibility and profitability. As described, the large-scale implementation of CCU technologies could, in the future, suffer from acceptance problems, particularly in the context of the already problematic perception of CCS technology. It is possible to address critical aspects and support objective, unbiased discussion on societal issues and assessment of CCU technology by means of distinguishing jointly developed and run communication strategies, with the inclusion of as many CCU-interested parties as possible.

Conclusions and recommendations for communication-related aspects of CCU technology:

- Carbon Capture and Utilisation (CCU) should be **clearly distinguished from CCS technologies** in communication processes with direct stakeholders and the general public alike, both technologically and contextually.

- Concrete ecological effects **must be evaluated on the basis of individual technologies and communicated accordingly.**

- Realistic presentation of the possibilities is, however, necessary, in particular, the limits of climatic and environmental effects through implementation of CCU technology in the most diverse and imaginable scenarios.

- In addition, it is the obligation of all CCU participants in science, economy and politics to participate in occupying **topical contexts and terminologies** which are not yet defined in public discourse, since the CCU field does not currently have any terminology which is used comprehensively across organisations.

- For this reason, as a communication basis, a **joint communication strategy** is recommended, along with the **development of guidelines** on relevant terms and topical frameworks, in order to create, both nationally and internationally, the prerequisites for unbiased discussion of further funding and implementation of CCU technology and to generate societal consciousness for topics such as (closed loop) recycling management or recycling and new technological ways to a more sustainable economy and society.

10.6. Possibilities for labelling of CO_2-based products

Even if there is currently still a great deal of uncertainties in the perspectives regarding labelling and several obstacles to be overcome in the further design and achievement of a certification for CCU products, there are still some recommendations that can be derived for representatives of industry in particular.

Conclusions and recommendations for finding a way to the certification of CCU products:

- Parties in industry and associations should already begin to consider and, if necessary, prepare the **development of regulations and certification options** in cooperation with experts from the fields of environmental protection and certification.

- Working out **joint interests** on the way to a certification as well as individual assessment of the options named by industry, associations and relevant areas of science, is unavoidable for the further development of the possibility of transparent labelling of CCU products.

- Within the scope of the perhaps necessary process of working out **Product Category Rules** (**PCR**) **for the CCU field in B2B**, the current status of scientific works on the topic of LCA must be taken into consideration in order to find sensible compromises to solve critical aspects in the methods – for example, in the form of selection of allocation criteria (please also refer to Chapter 4.).

- **Ease of understanding** must be guaranteed for certificate options for final consumers. In addition, the **international applicability** of possible options should be assessed and taken into consideration.

„Can CO_2 be recycled? A dialogue on Carbon Capture and Utilization (CCU)" on June 5th, 2014, at the IASS Potsdam. Here: Prof. Dr. Klaus Töpfer, IASS, with Dr. Christoph Gürtler, Dr. Karsten Malsch and Dr. Ulrich Liman, covestro AG (from left to right), with a sample of foam produced with CO_2.
© IASS/Christian Kruppa

This illustration is a "Graphic Recording" of the dialogue event "Can CO_2 be recycled? A dialogue on Carbon Capture and Utilisation (CCU) Technologies" held on June 5th 2014 at IASS Potsdam. The drawing contains different patterns of argumentation and questions that shaped the discussion. See also chapter 6.

11. Summary

This report presented, following a short introduction to CCU technology, a summary of the results of the project "CO_2 as Asset" at the Institute for Advanced Sustainability Studies (IASS Potsdam) and the cooperation project CO_2ntext. The presentation of the results is structured along the areas of competence ecology, economy, and communication. The section Communication additionally offers an overview of the events implemented within the scope of the project and other dialogue-centred measures. On the basis of the introduced works, the report also discusses interdisciplinary topics which interface with environmental policy, such as product labelling, distinction to CCS technologies, and possible interrelations between CCU and energy transition policies. In addition, recommendations are formulated for decision makers regarding the further treatment and development of CCU technology.

CCU technology can make a contribution to (closed loop) recycling management and to the securement of the resource base. **A contribution to climate protection is feasible here, but should not be overestimated. Within the scope of energy transition policies**, CCU technology, through its potential uses, could provide a technical option useful to the field of energy storage. Possible "path dependencies" to maintain the fossil energy generation structure can be avoided if emissions which result outside of the energy sector are used for CCU applications. The use of CCU technologies on a larger scale, for example **capture of CO_2** from flue gases of large fossil power stations, cannot currently be classified as being without cause for concern. Wherever feasible, higher concentrations of CO_2 sources should be used for the supply, which do not require the use of wet chemical absorption processes.

In order to evaluate the effects on the environment from individual CCU processes, the implementation of the LCA methodology (life cycle assessment) is recommended. General recommendations for the implementation of LCA for CCU, as well as first concrete life cycle assessments for individual CCU technologies, are already available. In order to achieve valid results for industrial practice, it is still necessary to, in particular, include the processes which are **upstream and downstream** of the CCU core process as well as developing **specific rules** for the implementation of CCU-related life cycle assessments under the same conditions, through a community of CCU interested parties.

Wide-scale implementation of CCU technology could potentially have various long-term **positive economic effects** such as, for example, synergy effects in production and reduced dependency on import of fossil resources. The potential to benefit society as a whole should be taken into consideration and evaluated within the decision-making processes and in the further promotion of the technologies. While some CCU-based products are already economically viable as a result of achieved increases in efficiency in production, some products, in particular fuels, are still not competitive in today's conditions. If an ecological benefit is foreseeable through the utilisation of these fuels, then incentives should consequently be created to support the success of these technologies in specific sensible areas of utilisation such as the ship or aerospace industry.

The success of technical innovations is also influenced by public acceptance, besides feasibility and profitability, on the part of the general public and consumers. CCU should be **clearly delimited from CCS technologies** in communication with both direct stakeholders and the general public, technologically and contextually. The possibilities, however, in particular also the limits of the climatic and environmental effects through implementation of CCU technology, must be **realistically presented** in diverse scenarios. Moreover, the usage of unified terminology is recommended for CO_2-utilisation technologies as far as is possible.

Parties in industry and associations should, already, begin to consider and, if necessary, prepare the **development of regulations and certification options** in cooperation with experts from the fields of environmental protection and certification in order to make CCU-based products recognisable as such. Existing certification systems offer first points of contact in this regard. Ease of understanding must be guaranteed for certificate options for **final consumers**. In addition, the **international applicability** of possible options should be assessed and taken into consideration.

In order to develop the sustainability potential of CCU as a contribution to (**closed loop**) **recycling management, securing raw materials and climate protection**, targeted support of political decision makers will be necessary in the course of further technological development and implementation. In particular, options for CO_2 capture and utilisation as a component within the context of a wider technological portfolio should be taken into consideration. To create the framework for the development of CCU technology, decision makers in politics, industry and science should consider the following aspects:

- Overall, research **funding** continues to make sense to accelerate the accomplishments of various interesting innovations. Here, possible ecological and economic benefits of the projects being funded should be taken into consideration.

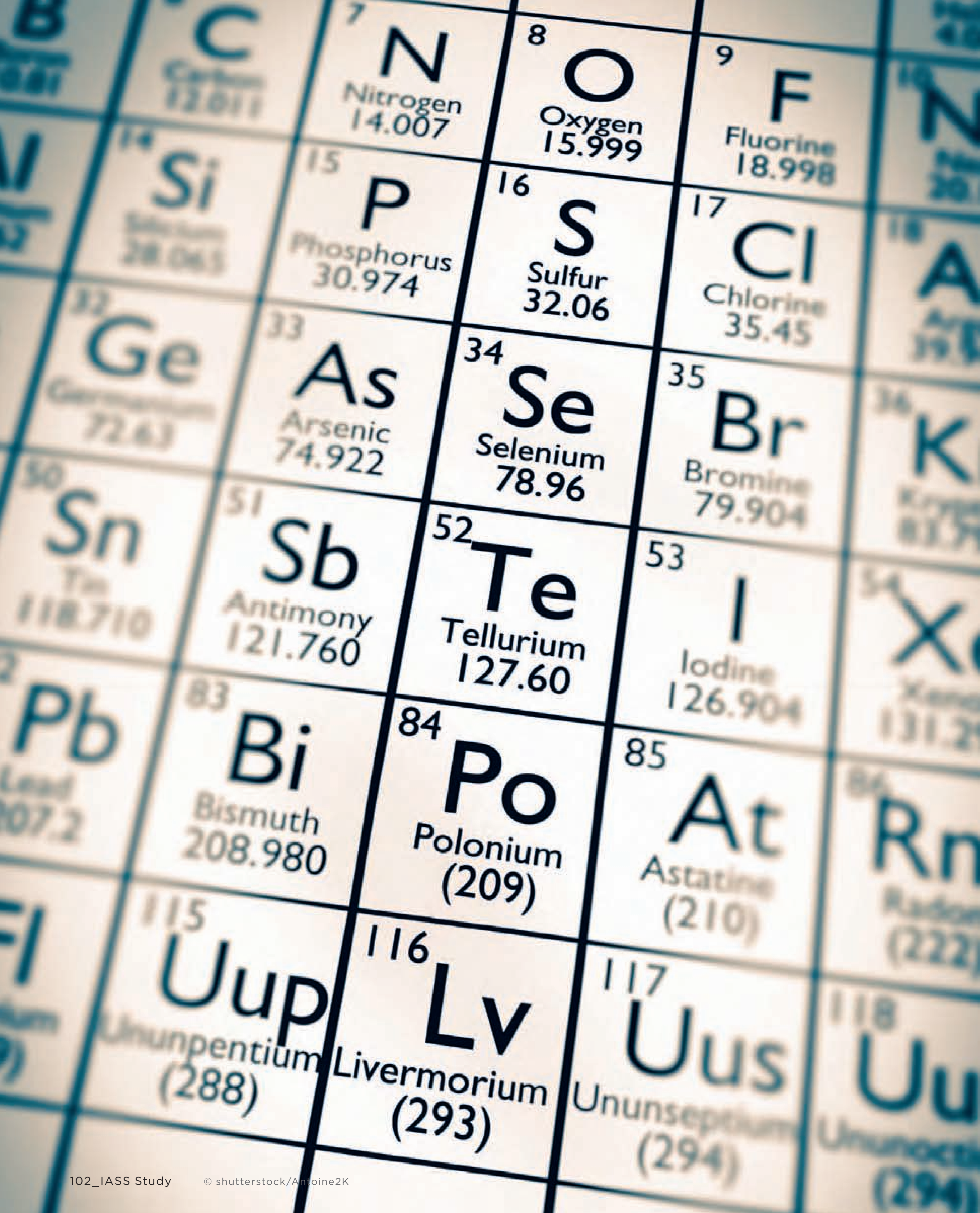
- **Path dependencies which lead to sustainment of fossil infrastructures** should be avoided in the development and implementation of CCU technology. The development of CCU technology should be supplementary to energy transition policies.

- CCU should only be calculated into climate-political measures such as **emission trading** in cases in which durable storage is proven (e.g. in building materials) as a direct emission reduction. Indirect calculation should be feasible with the existing emission reports and are to be clarified in detail for the concrete cases of individual plants and production chains.

The study represents, therefore, a comprehensive interdisciplinary alignment and assessment of the potential of CCU technologies, intended to broaden the view of technical and scientific parties and, at the same time, to offer an overview of societally relevant aspects of CCU to interested readers outside of the research and development environment. It describes a way in which CCU technologies can continue to be researched and implemented as sustainably as possible, drawing attention to the risks and obstacles which have to be taken into consideration.

“CO_2 recycling – option for politics and society? A dialogue on Carbon Capture and Utilisation (CCU) technologies” on November 9th, 2015, at IASS in Potsdam. Tea break in the institute's garden.

“Can CO_2 be recycled? A dialogue on Carbon Capture and Utilization (CCU)” on June 5th, 2014, at the IASS Potsdam. Here: Ralf Schmoll, Evonik, and Stefan Bringezu, Wuppertal Institut.


8
O
Oxygen
15.999
16
S
Sulfur
32.06
34
Se
Selenium
78.96
52
Te
Tellurium
127.60
84
Po
Polonium
(209)
116
Lv
Livermorium
(293)
7
N
Nitrogen
14.007
9
F
Fluorine
18.998
15
P
Phosphorus
30.974
17
Cl
Chlorine
35.45
33
As
Arsenic
74.922
35
Br
Bromine
79.904
51
Sb
Antimony
121.760
53
I
Iodine
126.904
83
Bi
Bismuth
208.980
85
At
Astatine
(210)
115
Uup
Ununpentium
(288)
117
Uus
(294)
Ge
Sn
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12. Glossary

Aerosols

Aerosols are solid or liquid particles suspended in a gas. They can be of natural origin, for example, pollen or mineral dust, or they can be residue from incineration such as soot. Secondary aerosols are particles which are formed in the atmosphere through the reactions of condensation nuclei.

Amines

"Amines" are molecules based on triple-bound nitrogen. They are, therefore, so-called organic derivatives of ammonia. Specific amines, for example Monoethalonamine (MEA) make up the main component of strong alkaline solutions which can be deployed for effective capture of CO_2 from flue gases.

Amine scrubbing

Amine scrubbing is a wet chemical washing process which can be used to capture CO_2 from flue gases with the aid of strong alkaline solutions. This procedure has been known and successfully employed since the 1930s. It is possible to retroactively upgrade existing industrial plants with chemical washing processes such as amine scrubbing ("Retrofit"). In the case of large-scale implementation of this process, an assessment of possible effects on the environment must still be carried out.

Anthropocene

The term "Anthropocene" originates from Earth System Science and was originally coined by scientists of the International Geosphere-Biosphere Programme (IGBP) around Will Steffen, Eugene F. Stoermer and Paul Crutzen. The term in based on the observation of grave changes in the indicators which serve to fully describe the Earth-ecological system. All these changes, according to the conclusions of the IGBP, can be attributed directly or indirectly to the effects of human intervention on the world-ecological system. The Earth is, therefore, no longer in the Holocene, but in the age of the human – the Anthropocene.

Capture

Within the scope of CCU technologies capture is understood as the process by which CO_2 is filtered out of industrial waste gases. The goal here is that, following the capture process, the CO_2 is available in sufficiently high purity in order to allow it to be used or geologically compressed.

Catalysis/catalysts

The term catalysis defines the act of influencing a chemical reaction with the aid of a catalyst, with the goal of initiating a reaction, accelerating a reaction or reducing the necessary energy for a reaction, as well as causing specific reaction processes. For CCU processes, breakthroughs in catalysis research were essential. They made first processes feasible and/or energetically sensible, thus enabling further processing on the inert material CO_2.

CCS/geological storage of CO_2

Carbon Capture and Storage defines the capture and subsequent geological storage of carbon dioxide from industrial waste gases, with the goal of removing CO_2 durably from the atmosphere. Storage is regarded as feasible, for example, in underground salt water layers and former crude oil and natural gas sites.

CCU – Carbon Capture and Utilisation or Carbon Capture and Use

The capture and utilisation of carbon dioxide in diverse production processes is referred to as "Carbon Capture and Utilisation (CCU)" or "Carbon Dioxide Utilisation" (CDU). This refers to technologies and processes which, either directly or following chemical transformation, use carbon dioxide as a component of a carbon dioxide compound in materials or energy carriers. CCU processes involve the capture and compaction of carbon dioxide, its transport (if necessary), and the separate functional utilisation of the CO_2 (von der Assen et al. 2013).

CCUS – Carbon Capture, Utilisation and Storage

In some countries, for example, in China and the USA, CCU and CCS are summarised under the joint generic term Carbon Capture, Utilisation and Storage" (CCUS). Both technology concepts are often treated jointly in research funding and scientific communication. The necessary differentiation is lost here.

Direct Air Capture/ Air Capture

Also the atmosphere can be used as a source of CO_2. Another approach, which is not yet commercially viable, plans to use chemical-technical procedures to filter CO_2 out of the atmosphere. These technologies, however, still require large amounts of energy and are, for this reason, expensive, but they are currently being tested on a pilot scale by some companies. For wide implementation, however, long-term technological advances are necessary.

(Closed loop) recycling management/ German Life-Cycle Resource Management Act (Kreislaufwirtschaftsgesetz)/ Recycling (Closed loop)

Recycling management defines a concept of leading resources that are completely utilised in production into further utilisation. Recycling processes are part of this concept, but are also supplemented by other forms of further use, such as cascade utilisation. In this study, both terms are used: (closed loop) recycling management stands for the conception of the objectives while recycling is a concrete process on the way to this. The European Guidelines for dealing with waste were determined by law in the German Life-Cycle Resource Management Act (KrWG) in 2012.

Direct use/direct utilisation of CO_2

The usage of carbon dioxide in industrial processes without chemical transformation is defined as direct utilisation of CO_2. This type of utilisation can take place in solid or liquid form and is already commonplace in diverse production processes, for example, carbonic acid in drinks, dry ice for cooling of foods, in fire extinguishers or as fertiliser in greenhouses.

End of life

The term "end of life" denominates the final phase in the life cycle of a product. This includes processes like the incineration of a product, its disposal on a landfill or its entering in a recycling process.

EOR/EGR – Tertiary Oil/Gas Recovery

Enhanced oil or gas recovery – (EOR/EGR) refers to procedures in which additional amounts of fossil fuels, following primary and secondary extraction, are extracted from oil and gas fields by means of injection of CO_2. The CO_2 then remains, in smaller or greater amounts, and for an undefined period of time, within the empty reserve.

Greenwashing

The term "greenwashing" denominates the deliberate exaggeration or the entirely false representation of a product's or a process' environmental characteristics. Greenwashing can be carried out by different actors, for example marketing departments of companies.

Life Cycle Assessment/ ecological balance/life cycle analysis

A Life Cycle Assessment or LCA is a systematic analysis of the possible effects on the environment of a production process of an interim or end product. Ideally, this analysis should include the complete lifetime of a product ("cradle to grave") or up to the point in time of the finished manufacture of an (interim) product ("cradle to gate"). For CCU products, this means, in particular, the inclusion of all of the processes upstream and downstream from the actual CCU core process, in order to make a holistic assessment of the possible effects on the environment possible.

Material utilisation of CO_2

CO_2, if chemically transformed, can serve as a raw material for the production of carbon compounds of energetically higher or of lower value. This so-called material utilisation of CO_2 as a component of materials, chemicals and minerals has been common for some time in special pharmaceutical products (e.g. headache tablets), solvents or, on the larger scale, fertilisers (urea). Furthermore, the material utilisation of CO_2 is already currently technically feasible in the manufacture of plastics and foams, paints and coatings, and building materials similar to cement (so-called minerals). These new procedures usually involve innovative processes to replace conventional production processes, but which are currently still in very early stages of development or have only recently become feasible due to breakthroughs in catalysis research, and which will now, first of all, have to be demonstrated on an industrial scale.

Minerals/mineralisation

Mineralisation is a process of material utilisation of CO_2, with the aid of which, for example, industrial waste such as ash and sand can be processed with CO_2 from waste gases to so-called minerals. Such minerals can be, for example, cement-like or other building materials similar to concrete for road works or other similar purposes.

Power-to-X/PtX/PtG/PtL

Power-to-X defines, as a generic term, all the processes which transform energy from renewable sources, for example, in the form of hydrogen or electricity, together with CO_2, to diverse energy sources (for example Power to gas – PtG, or Power to liquids – PtL). This technology plays an important role in the energy transition policies as an option for flexible deployment and sto-rage at peaks within the scope of the production of renewable energies, but is also open to other possibilities for large-scale application of CCU technology. Due to the low prices of fossil energy, these new technologies are, however, currently not competitive options to conventional fuels.

Stakeholders

Stakeholders are those individuals and groups that have material or immaterial claims towards any organisation and who have a reciprocal, multifaceted relationship of influence with that organisation. This relationship of influence can, but must not, include economic aspects.

13. References

Adamczewski, T. (2015). *Poland's approach to the Paris COP*, Heinrich-Böll-Stiftung, <https://www.boell.de/en/2015/11/24/background-polands-approach-paris-cop> [Accessed 25.10.2016]..

Ahn, H., Luberti, M., Liu, Z. & Brandani, S. (2013). Process Simulation of Aqueous MEA Plants for Post-combustion Capture from Coal-fired Power Plants, *Energy Procedia*, 37, 1523–1531.

AIChE (2016). *Carbon Capture Utilization and Storage*, <http://www.aiche.org/ccusnetwork> [Accessed Feb 16 2016].

Anastas, P. T., Warner, J.C. (1998). Principles of Green Chemistry, *Green Chemistry: Theory and Practice*, 29–56, <https://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry/principles/12-principles-of-green-chemistry.html> [Accessed 25.10.2016].

Aresta, M., ed.^eds. (2010). *Carbon dioxide as chemical feedstock*, Weinheim: Wiley.

Aresta, M., Caroppo, A., Dibenedetto, A. & Narracci, M. (2002). Life Cycle Assessment (LCA) applied to the synthesis of methanol. Comparison of the use of syngas with the use of CO_2 and dihydrogen produced from renewables. *In:* Maroto-Valer, M. M., Song, C. & Soong, Y., (eds.) *Environmental Challenges and Greenhouse Gas Control for Fossil Fuel Utilization in the* 21^{st} *Century*, Boston: Springer, 331–347.

Aresta, M. & Dibenedetto, A. (2010). Industrial utilization of carbon dioxide (CO_2), in Maroto-Valer, M. M., Hg., *Developments and innovation in carbon dioxide (CO_2) capture and storage technology: Volume 2: Carbon dixide (CO_2) storage and utilisation*, Great Abington: Woodhead Publishing, 377–410.

Aresta, M., Dibenedetto, A. & Angelini, A. (2013). The changing paradigm in CO_2 utilization. *Journal of CO_2 Utilization*, 3, 65–73.

Aresta, M. & Galatola, M. (1999). Life cycle analysis applied to the assessment of the environmental impact of alternative synthetic processes. The dimethylcarbonate case: part 1, *Journal of Cleaner Production*, 7(3), 181–193.

Armstrong, K. & Styring, P. (2015). Assessing the potential of utilisation and storage strategies for post-combustion CO_2 emissions reduction, *Frontiers in Energy Research*, 3.

Atkinson, R. (2000). Atmospheric chemistry of VOCs and NO_x, *Atmospheric Environment*, 34(12), 2063–2101.

Ausfelder, F. & Bazzanella, A. (2008). *Diskussionspapier Verwertung und Speicherung von CO_2* <http://www.dechema.de/dechema_media/diskussionco2.pdf> [Accessed 25.10.2016].

BBC (2015). *UK government carbon capture £1bn grant dropped*, <http://www.bbc.com/news/uk-scotland-scotland-business-34357804> [Accessed Jan 28 2016].

Bennett, S. J., Schroeder, D. J. & McCoy, S. T. (2014). Towards a Framework for Discussing and Assessing CO_2 Utilisation in a Climate Context, *Energy Procedia*, 63, 7976–7992.

Bloomberg (2013). *Norway Drops 'Moon Landing' as Mongstad Carbon Capture Scrapped*, <http://www.bloomberg.com/news/articles/2013-09-20/norway-drops-moon-landing-as-mongstad-carbon-capture-scrapped> [Accessed Feb 4 2016].

BMBF (2013). *Technologien für Nachhaltigkeit und Klimaschutz – Chemische Prozesse und stoffliche Nutzung von CO_2: Informationsbroschüre zur Fördermaßnahme des Bundesministeriums für Bildung und Forschung*, Bonn: BMBF.

BMBF (2015). *Bekanntmachung Richtlinie zur Förderung von CO_2Plus – Stoffliche Nutzung von CO_2 zur Verbreiterung der Rohstoffbasis*, <https://www.ptj.de/lw_resource/datapool/_items/item_6478/banz_at_25.06.2015_b4.pdf> [Accessed 25.10.2016].

BMWi (2016). *Existenzgründung*, Berlin: BMWi, <http://www.bmwi.de/DE/Themen/Mittelstand/Gruendungen-und-Unternehmensnachfolge/existenzgruendung.html> [Accessed 11.08.2016].

Borduas, N., Abbatt, J. P. D. & Murphy, J. G. (2013). Gas Phase Oxidation of Monoethanolamine (MEA) with OH Radical and Ozone: Kinetics, Products, and Particles, *Environmental Science & Technology*, 47(12), 6377–6383.

Boren, Z. D. (2016). *China's coal bubble -- 210 new coal-fired power plants were approved in 2015*, Greenpeace Energy Desk, 02.03.2016, <http://energydesk.greenpeace.org/2016/03/02/china-coal-bubble-210-power-plants/> [Accessed 27.10.2016].

Borkowski, M. G., Zaimes, G. G. & Khanna, V. (2012). Integrating LCA and thermodynamic analysis for sustainability assessment of algal biofuels: comparison of renewable diesel vs. biodiese, *2012 IEEE International Symposium on Sustainable Systems and Technology (ISSST)*, IEEE, 1–6.

Brandani, S. (2012). Carbon dioxide capture from air: a simple analysis, *Energy & Environment*, 23(2–3), 319–328.

Brekke, A., Askham, C., Modahl, I. S., Vold, B. I. & Johnsen, F. (2012). Environmental assessment of amine-based carbon capture: Scenario modelling with life cycle assessment (LCA), <http://ostfoldforskning.no/media/1165/1712.pdf> [Accessed 26.10.2016].

Brentner, L. B., Eckelman, M. J. & Zimmerman, J. B. (2011). Combinatorial life cycle assessment to inform process design of industrial production of algal biodiesel, *Environmental Science & Technology*, 45(16), 7060–7067.

Bringezu, S. (2014). Carbon Recycling for Renewable Materials and Energy Supply: Recent Trends, Long-Term Options, and Challenges for Research and Development, *Journal of Industrial Ecology*, 18(3), 327–340.

Bruhn, T., Naims, H. & Olfe-Kräutlein, B. (2016). Separating the debate on CO_2 utilisation from carbon capture and storage, *Environmental Science & Policy*, 60, 38–43.

Brunsting, S., Upham, P., Dütschke, E., Waldhober, M. D. B., Oltra, C., Desbarats, J., Riesch, H. & 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.

Bundesgesetzblatt (2012). KRWG Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschaftung von Abfällen (Kreislaufwirtschaftsgesetz). *In*: I, B. B. (ed.).

Campbell, P. K., Beer, T. & Batten, D. (2011). Life cycle assessment of biodiesel production from microalgae in ponds, *Bioresource technology*, 102(1), 50–56.

Canadell, J. G. & Raupach, M. R. (2008). Managing Forests for Climate Change Mitigation, *Science*, 320(5882), 1456–1457.

Carbon Capture Journal (2013). *Korea CCS center open 20 million $ innoivation challenge*, <http://www.carboncapturejournal.com/news/korea-ccs-center-opens-20-million-innovation-challenge/3283.aspx?Category=all> [Accessed 21.09.2016].

Carrington, D. (2016). *The Anthropocene epoch: scientists declare dawn of human-influenced age*, The Guardian, 29.08.2016, <https://www.theguardian.com/environment/2016/aug/29/declare-anthropocene-epoch-experts-urge-geological-congress-human-impact-earth> [Accessed 26.10.2016].

CEFIC (2016). *Extra-EU chemicals trade balance*, Brussels: CEFIC, <http://fr.zone-secure.net/13451/186036/?startPage=13#page=14> [Accessed 21.09.2016].

Climate-KIC (2014). *Climate-KIC to unveil multimillion Euro investment in four climate change innovation programmes at European Business Summit*, London: Climate-KIC, <http://www.climate-kic.org/press-releases/climate-kic-to-unveil-multimillion-euro-investment-in-four-climate-change-innovation-programmes-at-european-business-summit/> [Accessed 25.10.2016].

Cremer, C., Esken, A., Fischedick, M., Gruber, E., Idrissova, F., Kuckshinrichs, W., Linßen, J., Pietzner, K., Radgen, P. & Roser, A. (2008). *Sozioökonomische Begleitforschung zur gesellschaftlichen Akzeptanz von Carbon Capture and Storage (CCS) auf nationaler und internationaler Ebene: Endbericht*, Wuppertal: Wuppertal Institut für Klima, Umwelt, Energie GmbH.

Crutzen, P. J. (2002). Geology of mankind, *Nature*, 415(6867), 23–23.

Dai, N. & Mitch, W. A. (2015). Controlling Nitrosamines, Nitramines, and Amines in Amine-Based CO_2 Capture Systems with Continuous Ultraviolet and Ozone Treatment of Washwater, *Environmental Science & Technology*, 49(14), 8878–8886.

Daimler (2016). *Ausgezeichnete Klimaanlage: „Innovation der Vernunft“ Award für die CO_2 Klimaanlage von Mercedes-Benz*, Daimler AG, <http:http://media.daimler.com/marsMediaSite/de/instance/ko.xhtml?oid=9920162&ls=L3NlYXJjaHJlc3VsdC9zZWFyY2hyZXN1bHQueGh0bWw_c2VhcmNoU3RyaW5nPUtsaW1hYW5sY-WdlK0NPMiZzZWFyY2hJZD0xJnNlYXJjaFR5cGU9ZGV0YWlsZWQmYm9yZGVycz10cnVlJnJlc3VsdE-luZm9UeXBlSWQ9NDA2MjYmdmlld1R5cGU9bGlzdCZzb3J0RGVmaW5pdGlvbj1QVUJMSVNIRURfQVQt-MiZ0aHVtYlNjYWxlSW5kZXg9MCZyb3dDb3VudHNJbmRleD01&rs=3> [Accessed 25.10.2016].

Dautzenberg, G. & Bruhn, T. (2013). *Environmental impacts of carbon capture technologies: An overview of the state of development, potential side effects and current challenges for science and society*, IASS Working Paper, <http://www.iass-potsdam.de/sites/default/files/files/working_paper_environmental_impacts_of_carbon_capture_technologies_2.pdf> [Accessed 25.10.2016].

de Coninck, H. & Benson, S. M. (2014). Carbon Dioxide Capture and Storage: Issues and Prospects, *Annual Review of Environment and Resources*, 39(1), 243–270.

Delmas, M. A., Nairn-Birch, N. & Balzarova, M. (2013). Choosing the right eco-label for your product, *MIT Sloan Management Review*, 54(4), 10.

DIN (2009). *DIN EN ISO 14040: 2009–11: Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen (ISO 14040: 2006)*, Berlin: Beuth.

Eckl-Dorna, W. (2013). Warum Audi auf Öko-Gas setzt, *manager magazin online*, 28.07.2013, <http://www.manager-magazin.de/unternehmen/autoindustrie/kuenstliches-erdgas-audis-neue-strategie-fuer-die-autozukunft-a-908172.html> [Accessed am 12.08.2014].

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., C., M. J., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C. & Zwickel, T., Hg. (2014). *Climate change 2014: Mitigation of climate change*, New York: Cambridge University Press.

EEX (2015). *Market data: EEX Primary Auction Phase 3*, Leipzig: European Energy Exchange (EEX) AG, <http://www.eex.com/en/market-data#/market-data> [Accessed 25.10.2016].

enCO_2re (2016). *Want to know the CO_2 emissions streams in Europe and what purity they have? EnCO_2 re CO_2 visualisation tool*, <http://enipedia.tudelft.nl/EPRTR/CO2_source_visualization.html> [Accessed 26.10.2016].

Ericson, A., Bozzuto, C., Krutka, H., Tomski, P., Angielski, S. & Phillips, J. (2015). *Fossil Forward: Revitalizing CCS – Bringing Scale and Speed to CCS Deployment*, <http://www.nationalcoalcouncil.org/newsletter/Bridging_the_CCS_Chasm.pdf> [Accessed 18.02.2015].

European Commission (2003). *Integrated Product Policy-Building on Environmental Life-Cycle Thinking – Communication from the Commission to the Council and the European Parliament*, Document 52003DC0302, <http://ec.europa.eu/environment/ipp/ippcommunication.htm> [Accessed 25.10.2016].

European Commission (2016). *Carbon Capture and Geological Storage*, European Commission, <http://ec.europa.eu/clima/policies/lowcarbon/ccs/index_en.htm>[Accessed 28.02.2016].

European Commission & TNS (2011). Public Awareness and Acceptance of CO_2 capture and storage, *Special Eurobarometer*, 364, <http://ec.europa.eu/public_opinion/archives/ebs/ebs_364_en.pdf> [Accessed 26.10.2016].

European Commission & TNS (2013). Attitudes of Europeans towards building the single market for green products, *Flash Eurobarometer*, 367, <http://ec.europa.eu/public_opinion/flash/fl_367_en.pdf> [Accessed 16.10.2016].

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.

Fine, N. A., Goldman, M. J. & Rochelle, G. T. (2014). Nitrosamine Formation in Amine Scrubbing at Desorber Temperatures, *Environmental Science & Technology*, 48(15), 8777–8783.

Finlayson-Pitts, B.J. & Pitts, J. N. (1997). Tropospheric air pollution: ozone, airborne toxics, polycyclic aromatic hydrocarbons, and particles, *Science*, 276(5315), 1045–1051.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D. C. & Myhre, G. (2007). Changes in atmospheric constituents and in radiative forcing. *In:* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. & Miller, H. L., Hg., *Climate Change 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge: Cambridge University Press.

Freeman, R. E. (2004). The stakeholder approach revisited, *Zeitschrift für Wirtschafts- und Unternehmensethik*, 5(3), 228.

Fröndhoff, B. (2015). Die Welt hat kein Rohstoffproblem, *Handelsblatt*, Printausgabe, 21.10.2015.

GCCSI (2013). *CCUS development roadmap study for Guangdong Province, China*, Global CCS Institute, <https://hub.globalccsinstitute.com/publications/ccus-development-roadmap-study-guangdong-province-china/13-china-ccus-technology-development-roadmap> [Accessed 26.10.2016].

Gentry, P. R., House-Knight, T., Harris, A., Greene, T. & Campleman, S. (2013). Potential occupational risk of amines in carbon capture for power generation, *International Archives of Occupational and Environmental Health*, 87(6), 591–606.

Getzner, M., Spash, C. L. & Stagl, S., Hg. (2005). *Alternatives for Environmental Valuation,* Abingdon: Routledge.

Grunenberg, H. & Kuckartz, U. (2013). *Umweltbewusstsein im Wandel: Ergebnisse der UBA-Studie Umweltbewusstsein in Deutschland 2002*, Springer.

Guinee, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T. & Rydberg, T. (2010). Life cycle assessment: past, present, and future, *Environmental Science & Technology*, 45(1), 90–96.

Guinee, J. B., Heijungs, R. & van der Voet, E. (2009). A greenhouse gas indicator for bioenergy: some theoretical issues with practical implications, *The International Journal of Life Cycle Assessment*, 14(4), 328–339.

Haszeldine, R. S. (2009). Carbon capture and storage: how green can black be?, *Science*, 325(5948), 1647–1652.

Haszeldine, S. & Scott, V. (2011). Carbon capture: Why we need it, *New Scientist*, 210(2806), ii–iii.

Hauke, N. (2014). Die grüne Revolution an der Tankstelle? Die Relevanz politischer Narrative am Beispiel der Einführung des Biokraftstoffes E10. *In:* Gadinger, F., Jarzebski, S. & Yildiz, T., Hg., *Politische Narrative*, Wiesbaden: Springer, 173–197.

Hendriks, C., Noothout, P., Zakkour, P. & Cook, G. (2013). Implications of the Reuse of Captured CO_2 for European Climate Action Policies, <http://www.scotproject.org/sites/default/files/Carbon%20Count,%20Ecofys%20(2013)%20Implications%20of%20the%20reuse%20of%20captured%20CO2%20-%20report.pdf> [Accessed 14.08.2014].

Heo, J., McCoy, S. T. & Adams, P.J. (2015). Implications of Ammonia Emissions from Post-Combustion Carbon Capture for Airborne Particulate Matter, *Environmental Science & Technology*, 49(8), 5142–5150.

Horssen, A. V. (2011). *Air pollution impacts from carbon capture and storage (CCS)*, European Environment Agency.

IASS (2016). *CO_2 als Wertstoff (CCU) – Potenziale & Herausforderungen für die Gesellschaft*, IASS Potsdam, <http://www.iass-potsdam.de/de/forschung/technologischer-wandel/ccu> [Accessed 28.02.2016].

ICO_2N (2015). *Carbon Capture and Utilization*, <http://www.pembina.org/reports/ccu-fact-sheet-2015.pdf> [Accessed 25.10.2016].

IEA (2013). *Technology Roadmap: Carbon Capture and Storage – 2013 edition*, Paris: OECD/ IEA, <http://www.iea.org/publications/freepublications/publication/technologyroadmapcarboncaptureandstorage.pdf> [Accessed 25.10.2016].

IEA (2015). *Storing CO_2 through Enhanced Oil Recovery: Combining EOR with CO_2 storage (EOR+) for profit*, Paris: OECD/IEA, <https://www.iea.org/publications/insights/insightpublications/CO2EOR_3Nov2015.pdf> [Accessed 1.11.2016].

IEA Greenhouse Gas R & D Programme (2005). *A review of natural CO_2 occurences and releases and their relevance to C_2 storage*, (2005/8), <http://www.ieaghg.org/docs/General_Docs/Reports/2005-8.pdf> [Accessed September 2005].

IPCC (2014). *Climate Change 2014 – Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom and New York, USA.

ISIGE (2016). *CO_2 Capture, Storage and Utilization in China*, Institut Supérieur d'Ingénierie et de Gestion de l'Environnement, <http://www.isige.mines-paristech.fr/international-environmental-management-master/news/opportunities-for-co2-capture-storage-and-utilization-in-china> [Accessed 26.10.2016].

ISO (1999). *Environmental labels and declarations – Type I environmental labelling – Principles and procedures. ISO 14024:1999*, Genf: International Organisation for Standardisation.

ISO (2000). Environmental labels and declarations - General principles. ISO 14020:2000. *In:* Standardization, I. O. f. (ed.). Genf: International Organisation for Standardisation.

ISO (2002). Environmental management – Integrating environmental aspects into product design and development. ISO/TR 14062:2002, Genf: International Organization for Standardization.

ISO (2006a). Environmental labels and declarations – Type III environmental declarations – Principles and procedures. ISO 14025:2006, Genf: International Organisation for Standardisation.

ISO (2006b). Environmental management - Life cycle assessment – Principles and framework. ISO 14040:2006. *In:* ISO (ed.). Genf: International Organisation for Standardisation.

ISO (2006c). Environmental management – Life cycle assessment – Requirements and guidelines. ISO 14044:2006, Genf: International Organisation for Standardisation.

ISO (2015). Environmental management systems – Requirements with guidance for use. ISO 14001:2015. Genf: International Organisation for Standardisation.

ISO (2016). Environmental labels and declarations - Self-declared environmental claims - Type II environmental labelling. ISO 14021:2016. *In:* ISO (ed.). Genf: International Organisation for Standardisation.

Jensen, A. A., Hoffman, L., Møller, B. T., Schmidt, A., Christiansen, K., Elkington, J. & van Dijk, F. (1998). Life cycle assessment (LCA): A guide to approaches, experiences and information sources, *Environmental Issues Series*, 6(6), <file:///C:/Users/hma/Downloads/Issue-20report-20No-206.pdf> [Accessed 26.10.2016].

Jones, C. R. & Jones, A. R. (2016). Two Blind Mice: It Is Time for Greater Collaboration between Engineers and Social Scientists around the RDD & D of Industrial Technologies, *C – Journal of Carbon Research*, 2(2), 16.

Jones, C. R., Radford, R. L., Armstrong, K. & Styring, P. (2014). What a waste! Assessing public perceptions of Carbon Dioxide Utilisation technology, *Journal of* CO_2 *Utilization*, 7, 51–54.

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), 828–839.

Karl, M., Castell, N., Simpson, D., Solberg, S., Starrfelt, J., Svendby, T., Walker, S. E. & Wright, R. F. (2014). Uncertainties in assessing the environmental impact of amine emissions from a CO_2 capture plant, *Atmos. Chem. Phys.*, 14(16), 8533–8557.

Kätelhön, A., von der Assen, N., Suh, S., Jung, J. & Bardow, A. (2015). Industry-Cost-Curve Approach for Modeling the Environmental Impact of Introducing New Technologies in Life Cycle Assessment, *Environmental Science & Technology*, 49(13), 7543–7551.

Khakharia, P., Brachert, L., Mertens, J., Huizinga, A., Schallert, B., Schaber, K., Vlugt, T. & Goetheer, E. (2013). Investigation of aerosol based emission of MEA due to sulphuric acid aerosol and soot in a Post Combustion CO_2 Capture process, *International Journal of Greenhouse Gas Control*, 19, 138–144.

Kilimann, S. (2015). Klimaanlage auf der Anklagebank, *ZEIT Online*, <http://www.zeit.de/mobilitaet/2015-12/auto-klimaanlage-co2-klimaschutz-sicherheit> [Accessed 25.10.2016].

Kilisek, R. (2015). Why We Need to Get from Carbon Capture & Storage (CCS) to Carbon Capture & Utilization (CCU), *Breaking Energy*, 03.06.2015, <http://breakingenergy.com/2015/06/03/why-we-need-to-get-from-carbon-capture-storage-ccs-to-carbon-capture-utilization-ccu/> [Accessed 26.10.2016].

Klankermayer, J. & Leitner, W. (2015). Love at second sight for CO_2 and H_2 in organic synthesis, *Science*, 350(6261), 629–630.

Knudsen, S., Karl, M. & Randall, S. (2009). *Summary Report: Amine Emissions to Air during Carbon Capture, Phase I:* CO_2 *and Amines Screening Study for Effects to the Environment*, <http://co2.nilu.no/LinkClick.aspx?fileticket=m5iQCoa/Pqg=> [Accessed 26.10.2016].

Krämer, D., Roth, S. & Wunder, C. (2015). *Vom Abfall zum Rohstoff: Kann* CO_2 *in Zukunft Erdöl ersetzen?*, <https://www.bmbf.de/pub/Vom_Abfall_zum_Rohstoff.pdf> [Accessed 26.10.2016].

Lasch, H. (2014). Chance oder Scheindebatte? Kohlendioxid als Rohstoff, Ökotest, *Printausgabe*, 23.10.2014.

Le Quéré, C., Moriarty, R., Andrew, R., Peters, G., Ciais, P., Friedlingstein, P., Jones, S., Sitch, S., Tans, P. & Arneth, A. (2014). Global carbon budget 2014, *Earth System Science Data Discussions*, 7(2), 521–610.

Madsen, S., Normile-Elzinga, E. & Kinsman, R. (2014). *CO_2 based cleaning of commercial textiles: The world's first CO_2 solution for cleanroom textiles*, Littleton: CO_2 Nexus Inc, <http://www.energy.ca.gov/2014publications/CEC-500-2014-083/CEC-500-2014-083.pdf> [Accessed 25.10.2016].

Malvicino, C. (2011). *Final Report Summary - B-COOL (Low Cost and High Efficiency CO_2 Mobile Air Conditioning system for lower segment cars)*, European Commission, <http://cordis.europa.eu/result/rcn/46813_en.html> [Accessed 28.08.2015].

Markewitz, P., Kuckshinrichs, W., Leitner, W., Linssen, J., Zapp, P., Bongartz, R., Schreiber, A. & Muller, T. E. (2012). Worldwide innovations in the development of carbon capture technologies and the utilization of CO_2, *Energy & Environmental Science*, 5(6), 7281–7305.

McConnell, C. (2012). *Adding "Utilization" to Carbon Capture and Storage*, Washington: U.S. Department of Energy, <http://energy.gov/articles/adding-utilization-carbon-capture-and-storage> [Accessed 26.11.2014].

McKee, D., Hg. (1993). *Tropospheric ozone: human health and agricultural impacts*, Boca Raton: Lewis Publishers.

McNutt, M. K., Abdalati, W., Caldeira, K., Doney, S. C., Falkowski, P. G., Fetter, S., Fleming, J. R., Hamburg, S. P., , Morgan, M. G., Penner, J. E., Pierrehumbert, R. T., Rasch, P. J., Russell, L. M., Snow, J. T., Titley, D. W. & Wilcox, J. (2015). *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*, Washington, DC: The National Academies Press, <http://www.nap.edu/catalog/18805/climate-intervention-carbon-dioxide-removal-and-reliable-sequestration> [Accessed 26.10.2016].

Mennicken, L. (2015). The German R&D programme for CO_2 utilisation – an update, 5^{th} *Carbon Dioxide Utilisation Summit*, Dresden, 22.10.2015.

Mertens, J., Brachert, L., Desagher, D., Thielens, M., Khakharia, P., Goetheer, E. & Schaber, K. (2014). ELPI+ measurements of aerosol growth in an amine absorption column, *International Journal of Greenhouse Gas Control*, 23, 44–50.

Mertens, J., Knudsen, J., Thielens, M.-L. & Andersen, J. (2012). On-line monitoring and controlling emissions in amine post combustion carbon capture: A field test, *International Journal of Greenhouse Gas Control*, 6, 2–11.

Metz, B., Davidson, O., De Coninck, H., Loos, M. & Meyer, L. (2005). *IPCC special report on carbon dioxide capture and storage,* New York: Cambridge University Press, <http://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf> [Accessed 11.02.2015].

Mikkelsen, M., Jorgensen, M. & Krebs, F.C. (2010). The teraton challenge. A review of fixation and transformation of carbon dioxide, *Energy & Environmental Science*, 3(1), 43–81.

Naims, H. (2016). Economics of carbon dioxide capture and utilization – a supply and demand perspective, *Environmental Science and Pollution Research*, 1–16.

Naims, H., Olfe-Kräutlein, B., Lorente Lafuente, A. M. & Bruhn, T. (2015). *CO_2-Recycling – Option für Politik und Gesellschaft?*, IASS Potsdam, <http://www.iass-potsdam.de/sites/default/files/files/online_working_paper_1501214_hn.pdf> [Accessed 26.10.2016].

Nielsen, C., D'Anna, B., Dye, C., George, C., Graus, M., Hansel, A., Karl, M., King, S., Musabila, M. & Müller, M. (2010). *Atmospheric Degradation of Amines (ADA). Summary Report: Gas phase photo-oxidation of 2-aminoethanol (MEA)*, Kjeller: Norwegian Institute for Air Research, <file:///C:/Users/hma/Downloads/08-2010-CJN_MKA_ADA-report1.pdf> [Accessed 26.10.2016].

Norwegian Climate and Pollution Agency (2010). *Permit for activities pursuant to the Pollution Control Act for CO_2 Technology Centre Mongstad DA*, <http://www.tcmda.com/Global/Dokumenter/Klif_TCM_Discharge%20permit.pdf > [Accessed 26.10.2016].

NSF (2013). *RCNCCUS – Research Coordination Network Carbon Capture Untilization and Storage*, New York: NSF Science Engineering and Education for Sustainability, Columbia University, Lenfest Center for Sustainable Energy, <http://www.aiche.org/ccusnetwork> [Accessed 25.10.2016].

Oei, P., Kemfert, C., Reiz, F. & von Hirschhausen, C. (2014). *Braunkohleausstieg – Gestaltungsoptionen im Rahmen der Energiewende, Politikberatung kompakt*, Berlin: DIW.

Oettinger, G. (2011). CCS and CCU – A future for clean coal?, Speech at EUCERS EVENTS, <http://ec.europa.eu/commission_2010-2014/oettinger/headlines/speeches/2011/12/doc/20111212.pdf> [Accessed 01.02.2016].

Olfe-Kräutlein, B., Naims, H., Bruhn, T., Lorente Lafuente, A. M. & Tobias, M. (2014). *CO_2 als Wertstoff?*, IASS Fact Sheet, 2/2014, <http://www.iass-potsdam.de/sites/default/files/files/rz_fact_sheet_140708_digital_0.pdf> [Accessed 05.08.2016].

Otto, A., Grube, T., Schiebahn, S. & Stolten, D. (2015). Closing the loop: captured CO_2 as a feedstock in the chemical industry, *Energy & Environmental Science*, 8(11), 3283–3297.

Pan, S.-Y., Lorente Lafuente, A. M. & Chiang, P.-C. (2016). Engineering, environmental and economic performance evaluation of high-gravity carbonation process for carbon capture and utilization, *Applied Energy*, 170, 269–277.

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.

Piria, R., Naims, H. & Lorente Lafuente, A. M. (2016). *Carbon Capture and Utilisation (CCU): Klimapolitische Einordnung und innovationspolitische Bewertung*, <https://www.adelphi.de/de/publikation/carbon-capture-and-utilization-ccu-klimapolitische-einordnung-und-innovationspolitische> [Accessed 30.10.2016].

Raab, U. (2014). *Technical Expert Meeting on Carbon Capture, Use and Storage: Summary*, Bonn: United Nations Framework Convention on Climate Change (UNFCCC), <http://unfccc.int/files/bodies/awg/application/pdf/adp2-6_summary_report_ccus_for_posting.pdf> [Accessed 13.04.2016].

Raworth, K. (2012). A safe and just space for humanity: can we live within the doughnut, Oxfam Policy and Practice: *Climate Change and Resilience*, 8(1), 1–26.

Renn, O. (2005). Technikakzeptanz: Lehren und Rückschlüsse der Akzeptanzforschung für die Bewältigung des technischen Wandels, *Technikfolgenabschätzung – Theorie und Praxis*, 14(3), 29–38.

Reynolds, A. J., Verheyen, T. V., Adeloju, S. B., Meuleman, E. & Feron, P. (2012). Towards Commercial Scale Postcombustion Capture of CO_2 with Monoethanolamine Solvent: Key Considerations for Solvent Management and Environmental Impacts, *Environmental Science & Technology*, 46(7), 3643–3654.

Rochelle, G.T. (2009). Amine scrubbing for CO_2 capture, *Science*, 325(5948), 1652–1654.

Rockstrom, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sorlin, S., Snyder, P. K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R. W., Fabry, V. J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P. & Foley, J. A. (2009). A safe operating space for humanity, *Nature*, 461(7263), 472–475.

Rohr, A. & Knipping, E. (2011). *Health and Environmental Impacts of Amines for Post-Combustion Carbon Capture*, Workshop Summary, Palo Alto: Electric Power Research Institute (EPRI).

Santarius, T. (2012). *Der Rebound-Effekt: Über die unerwünschten Folgen der erwünschten Energieeffizienz*, Wuppertal: Wuppertal Institut.

Santos, S. (2015).CCS and CCU - Their role in the mitigation of greenhouse gas emissions from energy intensivs industry. *Methanol Technology and Policy Congress.* Frankfurt, Germany: IEAGHG.

Schramm, S. (2014). Unser umtriebiges Element, *ZEIT*, Printausgabe, 25.9.2014.

SCOT project (2016). *EU_ETS to incentivise CO_2 utilisation?*, SCOT Project Briefing Paper, <http://www.scotproject.org/images/Briefing%20paper%20EU%20ETS%20final.pdf> [Accessed am 26.10.2016].

Scott, V., Gilfillan, S., Markusson, N., Chalmers, H. & Haszeldine, R. S. (2013). Last chance for carbon capture and storage, *Nature Climate Change*, 3(2), 105–111.

Scott, V., Haszeldine, R. S., Tett, S. F. & Oschlies, A. (2015). Fossil fuels in a trillion tonne world, *Nature Climate Change*, 5(5), 419–423.

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.

Shah, A. D., Dai, N. & Mitch, W.A. (2013). Application of Ultraviolet, Ozone, and Advanced Oxidation Treatments to Washwaters To Destroy Nitrosamines, Nitramines, Amines, and Aldehydes Formed during Amine-Based Carbon Capture, *Environmental Science & Technology*, 47(6), 2799–2808.

Shao, R. & Stangeland, A. (2009). *Amines used in CO_2 capture – Health and environmental impacts*, Oslo: Bellona Foundation, <http://bellona.org/assets/sites/3/2015/06/fil_Bellona_report_September__2009_-_Amines_used_in_CO2_capture-11.pdf> [Accessed 26.10.2016].

Smit, B., Park, A.-H. A. & Gadikota, G. (2014). The Grand Challenges in Carbon Capture, Utilization, and Storage, *Frontiers in Energy Research*, 2, 55.

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O. & Ludwig, C. (2015). The trajectory of the Anthropocene: The Great Acceleration, *The Anthropocene Review*, 2(1), 81–98.

Steffen, W., Crutzen, P. J. & McNeill, J. R. (2007). The Anthropocene: are humans now overwhelming the great forces of nature, *Ambio: A Journal of the Human Environment*, 36(8), 614–621.

Steffen, W., Grinevald, J., Crutzen, P. & McNeill, J. (2011). The Anthropocene: conceptual and historical perspectives, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 369(1938), 842–867.

Steffen, W., Persson, Å., Deutsch, L., Zalasiewicz, J., Williams, M., Richardson, K., Crumley, C., Crutzen, P., Folke, C. & Gordon, L. (2011). The Anthropocene: From global change to planetary stewardship, *Ambio*, 40(7), 739–761.

Stephens, J. C. (2014). Time to stop investing in carbon capture and storage and reduce government subsidies of fossil-fuels, *WIREs Climate Change*, 5(2), 169–173.

Sternberg, A. & Bardow, A. (2015). Power-to-What? – Environmental assessment of energy storage systems, *Energy & Environmental Science*, 8(2), 389–400.

Strohbach, O. (2013). *World premiere: Audi opened power-to-gas facility*, Audi, <http://www.volkswagenag.com/content/vwcorp/info_center/en/themes/2013/06/Audi_opens_power_to_gas_facility.html> [Accessed 24.08.2015].

Styring, P., Jansen, D., de Coninck, H., Reith, H. & Armstrong, K. (2011). *Carbon Capture and Utilization in the green economy*, <http://co2chem.co.uk/wp-content/uploads/2012/06/CCU%20in%20the%20green%20economy%20report.pdf> [Accessed August 14, 2014].

Subcommission on Quaternary Stratigraphy (2016). *Working group on the 'Anthropocene'*, <http://quaternary.stratigraphy.org/workinggroups/anthropocene/> [Accessed 26.10.2016].

Tang, X., Price, D., Praske, E., Lee, S. A., Shattuck, M. A., Purvis-Roberts, K., Silva, P. J., Asa-Awuku, A. & Cocker Iii, D. R. (2013). NO_3 radical, OH radical and O_3-initiated secondary aerosol formation from aliphatic amines, *Atmospheric environment*, 72, 105–112.

TheLocal (2014). Vattenfall abandons research on CO_2 storage, *The Local*, 07.05.2014, <http://www.thelocal.se/20140507/vattenfall-abandons-research-on-co2-storage> [Accessed 25.10.2016].

Töpfer, K. (2013). Nachhaltigkeit im Anthropozän, *Nova Acta Leopoldina NF*, 117(398), 31–40.

UBA (2013). *Treibhausgasneutrales Deutschland im Jahr 2050 – Hintergrundpapier*, Dessau: Umweltbundesamt, <https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/treibhausgasneutrales_deutschland_im_jahr_2050_langfassung.pdf> [Accessed 25.10.2016].

UBA (2014). *Rebound-Effekte*, Dessau: Umweltbundesamt, <https://www.umweltbundesamt.de/themen/abfall-ressourcen/oekonomische-rechtliche-aspekte-der/rebound-effekte> [Accessed 25.10.2016].

UBA (2016). *Autoklimaanlagen mit klimaschonendem Kältemittel CO_2*, Dessau: Umweltbundesamt, <https://www.umweltbundesamt.de/themen/wirtschaft-konsum/produkte/fluorierte-treibhausgase-fckw/anwendungsbereiche-emissionsminderung/autoklimaanlagen-klimaschonendem-kaeltemittel-co2> [Accessed 25.10.2016].

UN Sustainable Development Knowledge Platform (2016). *Sustainable Development Goals*, New York: UN, <https://sustainabledevelopment.un.org/sdgs> [Accessed 11.08.2016].

University of Sheffield (2016). *Carbon Capture, Utilisation and Storage & Conventional Power*, Sheffield: University of Sheffield, <http://energy2050.ac.uk/research-facilities/energy-generation/carbon-capture-utilisation-and-storage/> [Accessed 26.10.2016].

UNOPS (2009). *A Guide to Environmental Labels – for Procurement Practitioners of the United Nations System*, Kopenhagen: United Nations Office for Project Services, <http://www.greeningtheblue.org/sites/default/files/Env%20Labels%20Guide_final_0.pdf> [Accessed 26.10.2016].

US DOE (o. D.-a). *Enhanced Oil Recovery, Washington*: U.S. Department of Energy, <http://energy.gov/fe/science-innovation/oil-gas-research/enhanced-oil-recovery> [Accessed 25.10.2016].

US DOE (o. D.-b). *Innovative concepts for beneficial reuse of carbon dioxide*, Washington: U.S. Department of Energy, <http://energy.gov/fe/innovative-concepts-beneficial-reuse-carbon-dioxide-0> [Accessed 20.01.2015].

US DOE & NETL (2010). *Carbon Dioxide Capture and Storage R&D Roadmap*, U.S. Department of Energy, National Energy Technology Laboratory, <https://www.netl.doe.gov/File%20Library/Research/Carbon%20Seq/Reference%20Shelf/CCSRoadmap.pdf> [Accessed 26.10.2016].

US DOE & NETL (2016). *CO_2 Utilization Focus Area*, U.S. Department of Energy, National Energy Technology Laboratory, <http://www.netl.doe.gov/research/coal/carbon-storage/research-and-development/co2-utilization> [Accessed 28.02.2016].

US EIA (2014). *Assumptions to the Annual Energy Outlook 2014*, Washington: U.S. Department of Energy, Energy Information Agency, <http://www.eia.gov/forecasts/aeo/assumptions/pdf/0554(2014).pdf> [Accessed 1.11.2016].

Varone, A. & Ferrari, M. (2015). Power to liquid and power to gas: An option for the German Energiewende, *Renewable and Sustainable Energy Reviews*, 45, 207–218.

Veltman, K., Singh, B. & Hertwich, E.G. (2010). Human and Environmental Impact Assessment of Postcombustion CO_2 Capture Focusing on Emissions from Amine-Based Scrubbing Solvents to Air, *Environmental Science & Technology*, 44(4), 1496–1502.

von der Assen, N., Jung, J. & Bardow, A. (2013). Life-cycle assessment of carbon dioxide capture and utilization: avoiding the pitfalls, *Energ. Environ. Sci.*, 6(9), 2721–2734.

von der Assen, N., Lampe, M., Müller, L. & Bardow, A. (2015). Life-Cycle Assessment Principles for the Integrated Product and Process Design of Polymers from CO_2, in Krist, V., Gerneay, J. K. H. & Rafiqul, G., Hg., *Computer Aided Chemical Engineering*, Amsterdam: Elsevier, 1235–1240.

von der Assen, N., Lorente Lafuente, A. M., Peters, M. & Bardow, A. (2015). Chapter 4 – Environmental Assessment of CO_2 Capture and Utilisation, in Armstrong, K., Styring, P. & Quadrelli, E. A., Hg., *Carbon Dioxide Utilisation*, Amsterdam: Elsevier, 45–56.

von der Assen, N., Müller, L. J., Steingrube, A., Voll, P. & Bardow, A. (2016). Selecting CO_2 Sources for CO_2 Utilization by Environmental-Merit-Order Curves, *Environmental Science & Technology*, 50(3), 1093–1101.

von der Assen, N., Sternberg, A., Kätelhön, A. & Bardow, A. (2015). *Environmental potential of carbon dioxide utilization in the polyurethane supply chain*, Faraday Discussions.

von der Assen, N., Voll, P., Peters, M. & Bardow, A. (2014). Life cycle assessment of CO_2 capture and utilization: A tutorial review, *Chemical Society Reviews*, 43(23), 7982–7994.

Wallquist, L., Visschers, V. H. & Siegrist, M. (2010). Impact of knowledge and misconceptions on benefit and risk perception of CCS, *Environmental Science & Technology*, 44(17), 6557–6562.

WBCSD (2014). *Life Cycle Metrics for Chemical Products: A guideline by the chemical sector to access and report on the environmental footprint of products, based on life cycle assessment*, <http://www.wbcsd.org/Pages/EDocument/EDocumentDetails.aspx?ID=16329> [Accessed 05.10.2015].

Wilcox, J. (2012). *Carbon capture*, New York: Springer.

Wilson, G., Travaly, Y., Brun, T., Knippels, H., Armstrong, K., Styring, P., Krämer, D., Saussez, G. & Bolscher, H. (2015). *A Vision for Smart CO_2 Transformation in Europe: Using CO_2 as a resource*, SCOT project, <http://www.scotproject.org/images/SCOT%20Vision.pdf> [Accessed 26.10.2015].

World Economic Forum (2014). *Towards the Circular Economy: Accelerating the scale-up across global supply chains*, Geneva: World Economic Forum, <http://www3.weforum.org/docs/WEF_ENV_TowardsCircularEconomy_Report_2014.pdf>[Accessed 28.11.2014].

Zero Emissions Plattform (2013). *CO_2 Capture and Use (CCU) – The potential to reduce CO_2 emissions and accelerate CCS deployment in Europe*, <file:///C:/Users/hma/Downloads/ZEP%20paper%20on%20CCU%20(2).pdf> [Accessed 28.02.2016].

Zimmermann, A. & Kant, M. (2016). *The Business Side of Innovative CO_2 Utilisation*, Berlin: EIT Climate KIC/TU Berlin, <http://enco2re.climate-kic.org/wp-content/uploads/2016/01/The-business-side-of-innovative-CO2-utilisation.pdf> [Accessed 11.08.2016].

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