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

Separating the debate on CO_2 utilisation from carbon capture and storage

Thomas Bruhn, Henriette Naims, Barbara Olfe-Kräutlein

Institute for Advanced Sustainability Studies, Berliner Str. 130, 14467 Potsdam, Germany

To address the urging challenge of climate change, the concept of Carbon Capture and Storage (CCS) plays a key role for keeping global warming below 2°C. Recently, the concept of Carbon Capture and Utilisation (CCU) has been a focus of growing attention with the aim of enabling an industrial utilisation of CO_2 as feedstock in the production of materials and fuels. Also in the pursuit of the ambitious targets set by the COP21 Paris agreement, CCU technologies could be discussed as an increasingly relevant means to meet mitigation targets. Often, CCU is commingled with the more prominent CCS and evaluated from the same perspective of climate change mitigation potential. Sometimes, the idea of utilising CO_2 as a resource is even used as an argument for investments in CCS. Despite some technological similarities, however, CCU and CCS address significantly different issues within the environmental policy debate. This paper analyses the commonalities and differences between CCU and CCS and recommends how one should be distinguished from the other, particularly in environmental policy fields and the public debate. Particularly, hopes that CCU could represent a promising perspective for contributing to mitigation efforts should not be exaggerated and considerations of CCU in climate politics need to account for the largely varying and technology specific temporary storage times of CO_2 and its specific substitution potential. Consequently, we call for accounting mechanisms and legislations for CCU that acknowledge the different storage durations and efficiency gains of CCU technologies.

Keywords:

CO_2 utilisation, CCU, CCS, resource security, energy transformation, climate change mitigation policy

1 Introduction

Carbon Capture and Storage (CCS) is widely discussed as an important means to reduce anthropogenic CO_2 emissions, particularly from large point sources such as fossil-fired power plants (Haszeldine and Scott, 2011; Scott et al., 2013; Scott et al., 2015). Recently, the concept of Carbon Capture and Utilisation (CCU) – also referred to as Carbon Dioxide Utilisation (CDU) or CO_2 Recycling – has been attracting greater attention with the aim of enabling an industrial utilisation of CO_2 as feedstock, for example, in the production of materials and synthetic fuels (Klankermayer and Leitner, 2015; McConnell, 2012; Müller et al., 2015; Oettinger, 2011; Peters et al., 2011). In public and political discussions, however, the two concepts are often commingled (McConnell, 2012; Oettinger, 2011; Smit et al., 2014).

Increasingly, CCU has also been receiving attention in the context of climate change mitigation and has been discussed together and in comparison with CCS (Izrael et al., 2013; McNutt, 2015; Metz et al., 2005). In the pursuit of the ambitious targets defined in the COP21 Paris agreement, CCU could hence represent a potential building block for a larger climate change mitigation strategy. For example, CCU could be explicitly included in the future design of the European emission trading system's innovation fund (NER.com, 2015). Poland for example even formulated hopes for CCU as a technological strategy to meet their mitigation targets without facing the need to phase out the use of coal too rapidly (Adamczewski, 2015; Jamieson, 1996). Moreover, the European Commission and the U.S. Department of Energy are promoting CCU to support the development and deployment of CCS, arguing that CCU improves the business case for CCS (McConnell, 2012; Oettinger, 2011).

As we will describe in this paper, such a commingling of CCU and CCS fuels misunderstandings or false expectations that can be counterproductive for the further development of CCU. Given their differences the two technologies should be treated significantly different in public debates and policy processes in order to prevent the emergence of strategic agendas that do not meet the specific requirements of the respective concepts.

In the following, we will first provide a brief overview on the well-established concept of CCS and a more detailed overview on the comparably less familiar concept of CCU before exploring the differences and commonalities of the two and potential issues due to their commingling. Based on this analysis we will then elaborate on the implications for the further treatment and discussion of the two concepts in the public debate and environmental policy.

2 CCS as a climate change mitigation option

Fossil-fired power and industrial plants contribute substantially to anthropogenic CO_2 emissions. In 2005, the IPCC estimated that the 8 000 largest point sources account for roughly 40% of total anthropogenic CO_2 emissions (14 Gt per year) (Metz et al., 2005). Against this background, the concept of CCS was developed, whereby CO_2 is separated from the flue gas of point sources and stored underground (Fig. 1).

IPCC mitigation scenarios for RCP 2.6 estimate that CCS from fossil- ("clean coal") and bioenergy-fired power plants (BECCS) could jointly contribute to a CO_2 emissions reduction of up to 25% by the year 2100 (IPCC, 2014). Thus, CCS is recognized as a mitigation instrument and has gained significant attention from governments, the fossil industry and important other players such as the IEA. While CCS development and implementation is still very slow and backlashes can be observed repeatedly (BBC, 2015; Bloomberg, 2013; TheLocal, 2014), the concept still remains an intention on many political agendas (DOE, 2016b; EC, 2016; GCCSI, 2013b; IPCC, 2014).

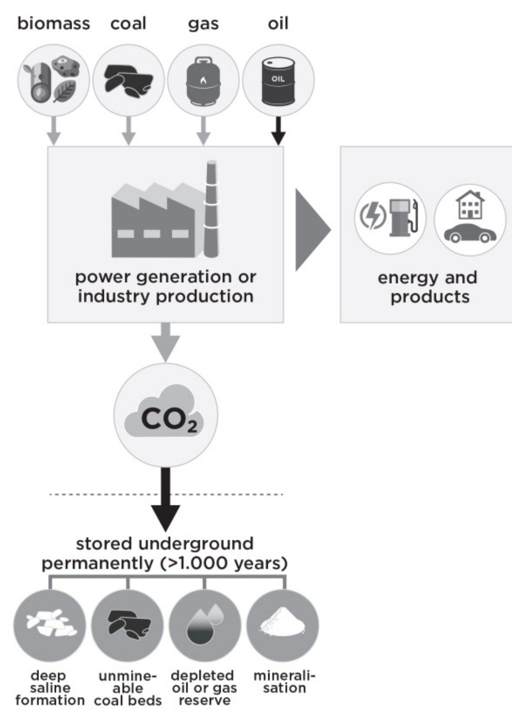

Figure 1: CCS – Storing CO_2 emissions underground
In CCS, CO_2 emissions from industrial flue gases are captured and then sequestered permanently underground.

While CCS is an accepted mitigation option in the EU Emission's Trading Scheme and the Clean Development Mechanism, the low allowance price has so far not created a business case for CCS itself (Haszeldine, 2009). Instead, the high costs (currently approximately USD 60–125 per ton of CO_2 avoided) (de Coninck and Benson, 2014) that stem from the significantly reduced efficiency of the power plants have been a major obstacle to the deployment of CCS. Nevertheless, the "clean coal" promise remains a tempting alternative for energy providers. This motivation behind CCS is often criticized for its potential to prolong the industry's business model instead of strengthening efforts to phase out of fossil fuels and develop renewable energies (Stephens, 2014). Since the safety and permanence of geological storage of CO_2 are still perceived to be uncertain, CCS has encountered public opposition in some countries (Brunsting et al., 2011; de Coninck and Benson, 2014; Selma et al., 2014). Consequently, due to a spectrum of reasons ranging from technical difficulties, lacking business cases and public opposition, CCS demonstration plants across Europe have largely been cancelled or postponed.

3 CCU as a resource security option

The concept of utilising CO_2 to produce materials was developed in chemical research in the 1970s, before climate change entered the public debate (Aresta, 2010). For a long time, several industrial sectors, including the chemical industry, relied on oil in particular for their production basis. Over the last decades, fossil resources have become an increasingly important cost competitiveness factor, while concerns about the environmental footprint of consumption have been rising. In this context, interest in unconventional sources of carbon as alternatives to oil, coal, and gas has grown.

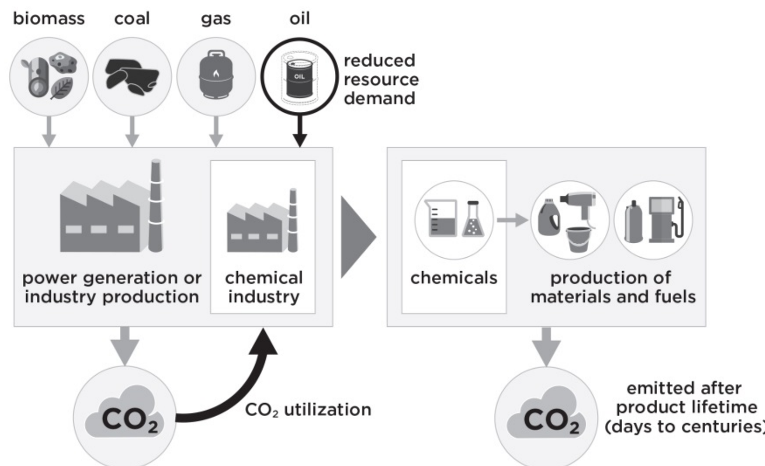

Figure 2: CCU – Using CO_2 to substitute fossil carbon sources
In CCU, CO_2 is used as resource, e.g., for the production of chemicals and materials, and can at least partially replace conventional fossil resources. Through this substitution the resource base of the respective industry is enhanced and the demand for fossil resources reduced. The storage of CO_2 in these products is only temporary and the CO_2 is usually emitted to the atmosphere at the end of the respective product's lifetime.

In principle, the utilisation of CO_2 is unattractive because of the CO_2 molecule's very low energy level. Recent catalysis research has, however, succeeded in demonstrating chemical reactions in which CO_2 is an efficient partial replacement for crude oil in the production of chemicals with a higher energetic value (Aresta, 2010; Mikkelsen et al., 2010; Peters et al., 2011; Styring et al., 2011). In such processes, CO_2 emissions can be utilised to produce a variety of chemicals, i.e., materials and energy carriers, such as plastics and liquid or gaseous fuels (Fig. 2). In these applications the utilised CO_2 is chemically altered and ends up in a new molecule. Meanwhile in other applications the CO_2 can be used directly i.e. without a chemical transformation and with a positive environmental impact replace various substances (Aresta and Dibenedetto, 2010; Madsen et al., 2014; Malvicino, 2011).

The CO_2 required for these utilisation options can be obtained from different kinds of sources including large emitting plants as well as smaller local industrial chimneys (von der Assen et al., 2016). For the business case of CCU, the utilised CO_2 must be cheaper than the conventional fossil carbon source. Since costs largely depend on the purity of the available CO_2 source and the efficiency of the chemical process, economic viability is technology-dependent.

Most CCU technologies do not allow for long-term storage of CO_2. After a certain time, the CO_2 incorporated into the product will be emitted into the atmosphere. Depending on the products lifetime the CO_2 thus can be stored from days or weeks (e.g. in liquid fuels) to years (e.g. in polymers) or even decades to centuries (e.g. in cement) (Styring et al., 2011; von der Assen et al., 2013). Those CCU technologies allowing a long-term storage of CO_2 can be justified to be considered as direct climate change mitigation measure if the CO_2 storage is monitored just as demanded by CCS regulation.

Similarly, also the total amounts that could be utilised vary significantly between the different kinds of CCU technologies. Even highly optimistic estimates currently assume that the total amount of CO_2 that could be utilised for CCU will be rather small – approximately 180 Mt (~0.5%) for chemicals and 2 Gt (~5.5%) for fuels – compared to total anthropogenic emissions of around 37 Gt of CO_2 in 2014 (Le Quéré et al., 2014; VCI and DECHEMA, 2009). Especially in comparison to the IEA CCS targets of 7 Gt of CO_2 stored annually by 2050, the CCU potential particularly for chemicals seems rather small (IEA, 2013). Hence, the magnitude of the amount of CO_2 that must be captured to meet CO_2 emission reduction goals is much greater than the potential of economic uses (Ericson et al., 2015). Moreover, the estimates for the potentially *used* emissions must be differentiated from the actually *reduced* emissions since all conversion technologies require energy. For each technology, the reduction potential thus needs to be determined individually and can be smaller or larger than the amounts of CO_2 used depending on the specific substitution potential and energy required. Consequently, CCU technologies per se do not permit the primary strategic ambition to contribute significantly to mitigating climate change but rather need to be considered as a component in a larger mitigation strategy.

So far, it has been demonstrated that CCU technologies can – but do not necessarily – have positive effects on the environment (Cuéllar-Franca and Azapagic, 2015; Sternberg and Bardow, 2015; von der Assen and Bardow, 2014). It needs to be noted, however, that these positive effects may manifest in benefits that are not primarily related to climate, for example avoiding the environmental risks and side-effects associated to exploitation and processing of fossil resources such as crude oil if CO_2 can be used as substitute for their derivative products (von der Assen and Bardow, 2014). The potential environmental benefits for the climate thus are more indirect effects since they will largely stem from the amounts of fossil raw materials that are substituted or from a reduction in consumed process energy (von der Assen et al., 2013). Thus, the environmental benefits correspond more to those of resource efficiency measures. Lifecycle analysis (LCA) can be useful to determine whether a specific CCU technology improves the overall environmental footprint of a given product (again not only the CO_2 footprint). Recent LCA results demonstrate that CO_2-based polyols for example exhibit a 13 to 16% reduction in fossil resource consumption compared to conventionally produced polyols. With respect to climate impacts, due to this substitution of fossil raw materials, the emission of up to three tons of CO_2 can be prevented for every input ton of CO_2 in polyol production.(von der Assen and Bardow, 2014) This illustrates how CCU can decrease the CO_2 footprints of conventional products by replacing fossil resources which have a large CO_2 footprint and hence combine economic and ecologic benefits. An LCA-based framework for assessing the environmental impacts of CCU technologies is currently under discussion (von der Assen et al., 2013).

The sustainability potential of CCU technologies thus can predominantly lie in enhancing resource security and preventing fossil related environmental side effects rather than in contributing strongly to climate change mitigation. Since the availability of energy from renewable sources is a prerequisite for the production of CO_2-based fuels in particular, CCU can also be pursued as a supplement to an energy transformation where it does not foster dependency on fossil resources (Olah, 2005).

4 Discussion: CCU and CCS – some shared ideas but different targets

4.1 Clarifying differences and commonalities between CCU and CCS

The following aspects highlight the most important conceptual commonalities and differences of CCS and CCU. To differentiate the specific potentials and societal contexts of the two concepts will help to prevent further commingling, develop efficient policy instruments and foster public acceptance of the desired technological state.

a) *Motivation*: CCS aims at climate change mitigation through less emission-intensive combustion of fossil resources and is essentially developed by the power sector and – less prominently – by the emission intensive industries such as aluminium or steel (EDIE, 2015; GCCSI, 2013a). CCU, by contrast, aims to reduce fossil resource consumption by reusing emitted CO_2 as substitute for conventional fossil carbon sources and is largely developed by the chemical industry.
b) *Technologies*: In both cases, CO_2 capture is the first technological step. In the second step, the CO_2 is either utilised directly or via technologies such as catalytic conversion (CCU) or inserted in geologic formations using storage technologies (CCS).
c) *Borderline*: There are two important technological options at the borderline of CCU and CCS which can entail both long-term CO_2 storage and utilisation purposes. For Enhanced Oil Recovery (EOR), captured CO_2 is pumped into geological formations to increase the amount of drilled oil. Furthermore, mineralization is often assigned to both concepts. A distinction is possible on a case by case basis when differentiating between the purposes of the minerals, which can be either for permanent storage in a reservoir or an industrial use e.g., as cement in the construction sector. For these borderline cases to count officially as CCS however, the respective long potential time-scales of storage (i.e. product lifetime) need to be made explicit and monitored consequently (Metz et al., 2005).
d) *Evolution*: Both concepts evolved in the context of the 1970s oil crises. At that time, CCS technologies were first applied in EOR. It was only from the late 1980s onwards that they began to be considered as a climate change mitigation option (Metz et al., 2005). Support for technical research on CCU grew as the debate about CO_2 emissions and waste reduction gained momentum (Aresta, 2010).
e) *Sources of CO_2*: Effective CCS targets large quantities and thus requires captured CO_2 from large point sources or ambient air. In the case of CCU, by contrast, the CO_2 demand is limited by the production amounts of the respective chemicals and regionally distributed. Thus, CO_2 sources

can be local industrial plants of various scales, which provide highly concentrated CO_2 at a comparatively low price (IEA and UNIDO, 2011).

f) *The fate of CO_2*: In the case of CCS, CO_2 is meant to be stored permanently, i.e., for more than a thousand years (Metz et al., 2005). In the case of CCU, CO_2 is stored only temporarily and emitted usually to the atmosphere at the end of the product's life, which can range from days or weeks (e.g. CO_2-based fuels) to years (e.g. CO_2-based polymers) or even decades or longer (e.g. CO_2-based cement). Due to this difference, it is not sufficient to assess CCU concepts with respect to the amounts of CO_2 that can be *utilised* but rather it is essential to determine the overall CO_2 *reduction* and storage *duration*.

g) *Sustainability potential*: CCS is thought to have a great potential to contribute to CO_2 mitigation and is important in IPCC scenarios. The combination of Bio-Energy with CCS (BECCS) in particular seems essential to achieving net negative emissions after 2050 (IPCC, 2014). Critics of CCS from fossil power claim, however, that it might counteract the deployment of renewables and shift the environmental costs of today's emissions onto future generations (Greenpeace, 2008, 2011; ZERO, 2015). By contrast, CCU has a limited and predominantly indirect abatement potential and is not considered as relevant for mitigation scenarios. In the aftermath of the ambitious targets set out by the COP21 Paris agreement, however, CCU could further be considered as one building block in a portfolio of mitigation measures. Moreover, CCU could potentially support the energy transformation by enabling energy storage through power-to-liquid or power-to-gas approaches and contributing to a circular economy by converting waste emissions into a resource.

h) *Incentives*: There are currently very few economic incentives for the deployment of CCS. In the future, however, regulation such as emission performance standards could make CO_2 removal mandatory. Yet in CCU, individual business cases are already providing incentives for different actors today. A higher price for emission allowances could further strengthen the incentives for both CCU and CCS.

i) *Added Value*: In the case of CCS, the added value is negative due to the costs of capture and storage and the increased primary energy demand. In the case of CCU, added value can be positive as a result of the cost savings from fossil raw material reduction. If the capture costs can be minimized, CO_2 can be given a value and transformed from a liability into an asset.

4.2 Observed problems arising from a commingling of CCU and CCS

All over the world it can be observed that CCU and CCS are frequently commingled in various political contexts (AIChE, 2016; ISIGE, 2016; UoS, 2016). The U.S. Department of Energy (DOE) for example lists CCU as a subcategory of CCS and the research communities are connected in the joint network "CCUS" (Carbon Capture Utilization and Storage) (AIChE, 2016; DOE, 2016a, b). Also, major research reports evaluate CCU as a subcategory of CCS (McNutt, 2015; Metz et al., 2005). Given that CCU and CCS both avail of capture technologies, especially in the early development stages, a commingling of the two concepts can be justified to a certain extent. However, as the technologies mature to greater readiness, the different underlying ideas and the strategic goals they can serve gain relevance and their commingling brings along several problems.

One of the consequences of this commingling is, for example, that several experts and stakeholders tend to assess CCU primarily with respect to its potential to contribute to climate change mitigation (Hendriks et al., 2013; Markewitz et al., 2012; Oei et al., 2014). Often, a narrative is selected that presents CCU as an *alternative* to CCS following the imperative that instead of storing CO_2 underground, it should be targeted to close the carbon cycle with the help of CCU (Armstrong and Styring, 2015; Kilisek, 2015). As a consequence of such a framing, it has been observed that many stakeholders in the political debate in Germany are sceptical or even negative about CCU because of its limited potential to contribute to climate change (Lasch, 2014). However, as argued a major share of the reasons to be interested in CCU is not directly related to climate change (Bennett et al., 2014; von der Assen et al., 2013). In addition, media reports often tend to pick the most optimistic expert estimates available when depicting CCU which might incentivize scientists to exaggerate their findings (Fröndhoff, 2015; Lim, 2015). A further commingling of CCU and CCS therefore fosters the effect that CCU is predominantly considered with respect to its mitigation potential while disregarding the other potential strategic environmental contributions of CCU.

Another issue is that CCU is often communicated as a means to foster the deployment of CCS (Ericson et al., 2015; Mikkelsen et al., 2010; Styring et al., 2011; Zero Emissions Plattform, 2013) and it is widely argued that CCU can help to improve the business case of CCS application in the early stages of development (Santos, 2015; Zero Emissions Plattform, 2013). This framing of CCU, however, can lead to the perception that CCU and CCS share a joint strategic potential. Particularly those stakeholders critical towards CCS consequently tend to transfer their critical attitude onto CCU due to this commingling, as observed in a stakeholder dialogue series conducted by the authors (IASS, 2016; Naims et al., 2015). Especially the deliberate communication of CCUS by the networks of the fossil power sector can trigger the impression that CCU entails another strategy to prolong the use of fossil-fired power generation and to prevent decarbonisation of the industry (Ericson et al., 2015; ICO2N, 2015; Zero Emissions Plattform, 2013). Consequently, CCU has for example been called a “fig-leaf” for CCS in the public opposition context (Lasch, 2014). Overall, these dynamics resulting from a commingling of CCU and CCS are not helpful for an impartial assessment of CCU and hence could prevent the necessary public and political support for the further development and implementation of CCU.

4.3 Implications for environmental politics

The highlighted differences between CCS and CCU and the issues raised following their commingling suggest that the two concepts should be treated more separately in the ongoing political debates and address different protagonists and stakeholders in decision-making processes. To facilitate the development of informed opinions and tailored policy instruments, the specifics of both concepts must be acknowledged, especially in the following fields of environmental policy:

Climate protection: Unlike CCS, CCU should not be addressed primarily in the context of climate change mitigation. Framing CCU as a mitigation option leaves out important aspects of the concept’s original motivation and capacities. Accordingly, the potential of CCU to facilitate negative emissions should not be exaggerated. In any case, the varying but largely limited storage lifetime of CO_2 and potential indirect climate effects from raw material efficiencies need to be assessed on a case by case basis for specific

CCU approaches. Hence, commingling CCS and CCU in the term CCUS avoids this clarification and therefore fuels the depicted kind of misunderstandings. To avoid disappointment, CCU research should particularly not be framed as support for CCS deployment, as exemplified in statements by selected authorities worldwide (McConnell, 2012; Oettinger, 2011). Especially in the aftermath of the COP21 Paris agreement, CCU technologies are likely to be considered further for contributing to the ambitious emission reduction targets. Here, CCU can contribute through reducing process emissions and even possibly through negative CO_2 emissions to an extent that is defined and limited by the *accumulated storage capacity* resulting from the total amount of CO_2-based products in the market. Clarifying this total budget and developing mechanisms how to treat these in the post-Paris process will be essential tasks for the future.

Energy transformation: CCS has been proposed as a way to reduce the climate impact of continued fossil power generation at increased energy costs (IEA, 2013) Hence, it does not represent a step towards shifting the energy system away from fossil resources. CCU technologies, by contrast, aim to replace fossil resources and can thus support a transformation towards renewables and extend it to industries outside the energy sector such as transport and materials (Klankermayer and Leitner, 2015).

Resource security: While CCS supports existing resource strategies, CCU technologies offer an additional opportunity for resource management and recycling, as proposed by the vision of a circular economy (Bringezu, 2014; World Economic Forum, 2014). Thus, CCU technologies should be integrated into political resource security strategies and resource efficiency instruments.

Hence of these three fields, we consider resource security and energy transformation policies as most relevant for a further development of CCU. Both are predominately developed at national level. As the prospects of CCU depend on the specific resource base, technical expertise, and the industrial structure of a region, we recommend further political facilitation of CCU at national or regional level. The national post-Paris processes are expected be helpful in this regard.

5 Conclusion

In this paper, we have provided an analysis of the commonalities and differences between CO_2 utilisation and CCS and elaborated on how these are often commingled in the public and political discourse. Arguments have been presented as to why and how commingling CCU with the debate on CCS does not do justice to the specific characteristics of the two concepts and could be counterproductive for the further development particularly of CCU. Above all, we argue that a framing of CCU in the context of climate change mitigation does not meet the most important potentials of many CCU technologies and can even hinder the public and political support that is necessary for the further development. Rather we recommend addressing CCU primarily in the context of resource security and energy transformation both in the public and political debate.

Hopes that CCU could represent a promising perspective for contributing to national or international mitigation efforts should not be exaggerated. Especially, any consideration of CCU in climate politics needs to account for the largely varying substitution effects and lifetimes of CCU-based products which imply an only temporary storage of CO_2. Consequently, also legislations for CCU need to be tailored to acknowledge the different storage durations of different CCU technologies and their efficiency potentials. Developing mechanisms that allow for a transparent accounting of the mitigation potential of CCU for example on the basis of technology-specific LCA basis therefore seems a crucial task for the future.

6 Acknowledgement

The authors would like to thank the participants of the CCU Roundtable 2014 and 2015 for helpful discussions and impulses.

7 References

Adamczewski, T., 2015. Poland’s approach to the Paris COP. Heinrich Böll Stiftung.

AIChE, 2016. Carbon Capture Utilization and Storage.

Aresta, M., 2010. Carbon dioxide as chemical feedstock. Wiley, Weinheim.

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

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.

BBC, 2015. UK government carbon capture £1bn grant dropped.

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.

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, 327–340.

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, 1651-1662.

Cuéllar-Franca, R.M., Azapagic, A., 2015. Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. Journal of CO_2 Utilization 9, 82-102.

de Coninck, H., Benson, S.M., 2014. Carbon Dioxide Capture and Storage: Issues and Prospects. Annual Review of Environment and Resources 39, 243-270.

DOE, 2016a. CO_2 Utilization. U.S. Department of Energy.

DOE, 2016b. CO_2 Utilization Focus Area. U.S. Department of Energy.

EC, 2016. Carbon Capture and Geological Storage. European Commission.

EDIE, 2015. Cement and steel industries need 'urgent' introduction of CCS technologies. edie.net.

Ericson, A., Bozzuto, C., Krutka, H., Tomski, P., Angielski, S., Phillips, J., 2015. Fossil Forward: Revitalizing CCS - Bringing Scale and Speed to CCS Deployment. National Coal Council.

Fröndhoff, B., 2015. Die Welt hat kein Rohstoffproblem, Handelsblatt, Printausgabe.

GCCSI, 2013a. CCS for iron and steel production. Global CCS Institute.

GCCSI, 2013b. CCUS development roadmap study for Guangdong Province, China. Global CCS Institute.

Greenpeace, 2008. False Hope - Why carbon capture and storage won’t save the climate. Greenpeace, Amsterdam.

Greenpeace, 2011. CO_2-Endlager: Keine Lösung, sondern Risiko, In: Greenpeace (Ed.).
Haszeldine, R.S., 2009. Carbon capture and storage: how green can black be? Science 325, 1647-1652.
Haszeldine, S., Scott, V., 2011. Carbon capture: Why we need it. New Scientist 210, ii-iii.
Hendriks, C., Noothout, P., Zakkour, P., Cook, G., 2013. Implications of the Reuse of Captured CO2 for European Climate Action Policies. ECOFYS Netherlands B.V., Utrecht.
IASS, 2016. CO_2 als Wertstoff (CCU) - Potenziale & Herausforderungen für die Gesellschaft. IASS Potsdam.
ICO2N, 2015. Carbon Capture and Utilization.
IEA, 2013. Technology Roadmap: Carbon Capture and Storage - 2013 edition. OECD/ IEA, Paris.
IEA, UNIDO, 2011. Technology Roadmap - Carbon Capture and Storage in Industrial Applications. International Energy Agency (IEA) and the United Nations Industrial Development Organization (UNIDO).
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
Izrael, Y.A., Volodin, E., Kostrykin, S., Revokatova, A., Ryaboshapko, A., 2013. Possibility of geoengineering stabilization of global temperature in the 21st century using the stratospheric aerosol and estimation of potential negative effects. Russian Meteorology and Hydrology, 371-381.
Jamieson, D., 1996. Ethics and intentional climate change. Climatic Change 33, 323-336.
Kilisek, R., 2015. Why We Need to Get from Carbon Capture & Storage (CCS) to Carbon Capture & Utilization (CCU) Breaking Media, Inc.
Klankermayer, J., Leitner, W., 2015. Love at second sight for CO_2 and H_2 in organic synthesis. Science 350, 629-630.
Lasch, H., 2014. Chance oder Scheindebatte? Kohlendioxid als Rohstoff, Ökotest, pp. 18-26.
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, 521-610.
Lim, X., 2015. How to make the most of carbon dioxide, Nature.
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. CO_2 Nexus Inc, Littleton.
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.
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, 7281-7305.
McConnell, C., 2012. Adding "Utilization" to Carbon Capture and Storage. U.S. Department of Energy, Washington.
McNutt, M., et al., 2015. Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration. National Academy of Sciences Washington D.C. .
Metz, B., Davidson, O., De Coninck, H., Loos, M., Meyer, L., 2005. IPCC special report on carbon dioxide capture and storage. Cambridge University Press, New York.
Mikkelsen, M., Jorgensen, M., Krebs, F.C., 2010. The teraton challenge. A review of fixation and transformation of carbon dioxide. Energy & Environmental Science 3, 43-81.
Müller, T., Leitner, W., Markewitz, P., Kuckshinrichs, W., 2015. Opportunities for Utilizing and Recycling CO2, In: Kuckshinrichs, W., Hake, J.-F. (Eds.), Carbon Capture, Storage and Use. Springer International Publishing, pp. 67-100.
Naims, H., Olfe-Kräutlein, B., Lorente-Lafuente, A.M., Bruhn, T., 2015. CO_2-Recycling – Option für Politik und Gesellschaft? IASS Potsdam.
NER.com, 2015. Environment Ministers exchange views on NER400 Innovation Fund.

Oei, P., Kemfert, C., Reiz, F., von Hirschhausen, C., 2014. Braunkohleausstieg–Gestaltungsoptionen im Rahmen der Energiewende (Studie des Deutschen Instituts für Wirtschaftsforschung/DIW–Reihe Politikberatung kompakt). Berlin.

Oettinger, G., 2011. CCS and CCU - A future for clean coal?, Speech at EUCERS EVENTS. European Commission, Brussels.

Olah, G.A., 2005. Beyond oil and gas: the methanol economy. Angew. Chem. Int. Ed. 44, 2636-2639.

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, 1216-1240.

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

Scott, V., Gilfillan, S., Markusson, N., Chalmers, H., Haszeldine, R.S., 2013. Last chance for carbon capture and storage. Nature Climate Change 3, 105-111.

Scott, V., Haszeldine, R.S., Tett, S.F., Oschlies, A., 2015. Fossil fuels in a trillion tonne world. Nature Climate Change 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.

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

Stephens, J.C., 2014. Time to stop investing in carbon capture and storage and reduce government subsidies of fossil-fuels. WIREs Clim. Change 5, 169-173.

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

Styring, P., Jansen, D., de Coninck, H., Reith, H., Armstrong, K., 2011. Carbon Capture and Utilization in the green economy. Centre for Low Carbon Futures, York.

TheLocal, 2014. Vattenfall abandons research on CO_2 storage, The Local.

UoS, 2016. Carbon Capture, Utilisation and Storage & Conventional Power. University of Sheffield.

VCI, DECHEMA, 2009. Position Paper Utilisation and Storage of CO_2. Dechema, Frankfurt am Main.

von der Assen, N., Bardow, A., 2014. Life cycle assessment of polyols for polyurethane production using CO_2 as feedstock: insights from an industrial case study. Green Chemistry 16, 3272–3280.

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

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, 1093-1101.

World Economic Forum, 2014. Towards the Circular Economy: Accelerating the scale-up across global supply chains. World Economic Forum, Geneva.

ZERO, 2015. "Putting it back" - A series on storage of CO_2 (part 3)- Global NGO views on CCS and storage of CO_2. Zero Emission Resource Organisation

Zero Emissions Plattform, 2013. CO_2 Capture and Use (CCU) - The potential to reduce CO_2 emissions and accelerate CCS deployment in Europe.

CVs of the authors

Dr. Thomas Bruhn received a doctorate in physics from the Technical University of Berlin. He worked for the Leibniz institute for analytical sciences (ISAS) and joined the IASS Potsdam in 2012 after research stays at University "Tor Vergata" in Rome (Italy) and the Interdisciplinary Centre for Nanosciences

(CiNaM) in Marseille (France). At the IASS Potsdam his research focusses on environmental impacts of carbon capture technologies and stakeholder engagement on climate engineering. Beside his research, he is active as a member to the thinktank30 of the Club of Rome and a member of the board of directors of the Global Contract Foundation.

Henriette Naims completed a triple diploma program in international business studies and holds degrees by the European University Viadrina Frankfurt /Oder (Germany), the ESC Montpellier (France) and the Manchester Metropolitan University (UK). After several years of work experience in strategy and consulting divisions of the media and communication industry she joined the IASS Potsdam in 2013 to research on the economics of environmental innovations and technologies and their industrial value chains. She is a PhD candidate at the School of Business and Economics at Freie Universität Berlin.

Dr. Barbara Olfe-Kräutlein graduated in Media and Communication Studies, Islamic Studies and Arab Literature at the Freie Universität Berlin, where she also gained her doctoral degree with her thesis on political communication processes in the DAX companies' representative offices in the German capital in 2003. After working a few years as communication specialist in the industry, she joined the IASS Potsdam in 2013 to research on communication aspects and societal acceptance of complex and innovative sustainable technologies.