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Conflicting expectations on carbon dioxide utilisation

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ABSTRACT
To utilise carbon dioxide as a resource rather than treating it only as a polluting greenhouse gas is gaining increased attention. Expectations on the future capabilities of technologies that could make utilisation of carbon dioxide possible are currently raised in scientific literature. These are in important ways shaping the development process by defining what is possible and desirable to develop. Building on sociology of expectations, we show how some of these expectations are in conflict. The most notable expectation of carbon dioxide utilisation is that it will contribute to mitigation of climate change, but at the same time there are conflicting expectations regarding suitable applications, requirements on feedstock and energy use, and how the concept should be framed in relation to other technologies. These conflicting expectations show how different types of actions are encouraged, and how technologies related to seemingly similar goals could result in very different levels of greenhouse gas emissions and thereby climate change impact.

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1. Introduction

Carbon dioxide is the most abundant greenhouse gas and the largest contributor to climate change, but it can also be utilised as a carbon feedstock. Carbon dioxide is currently used both in direct applications such as fire extinguishers, soft drinks, dry blasters, and converted into more advanced end products such as fertilisers, fuels and materials (Naims 2016). Research exploring a wide range of applications has emerged, such as drop-in plastics (Palm, Nilsson, and Åhman 2016), concrete with a lower climate impact (Monkman and MacDonald 2017) alongside the established practice of using carbon dioxide for enhanced oil recovery (Godec, Kuuskraa, and Dipietro 2013). One of the starting points for developing carbon dioxide utilisation was recovery of carbon dioxide from fossil flue gas as a means to mitigate climate change. Both permanent fixation and short time utilisation were suggested (Aresta, Quaranta, and Tommasi 1992). With growing societal concern over climate change, the interest in carbon dioxide utilisation is now gaining increased attention. Its potential to contribute to mitigation of climate change has led to large research funding in the EU Research and Innovation Programme, and in the upcoming Innovation Fund for demonstration of innovative low-carbon technologies (European Commission 2018; European Commission 2020), and on the national level (e.g. UK Department for Business, Energy & Industrial Strategy 2018). In the Innovation Fund, carbon dioxide utilisation is highlighted as one of the five prioritised areas that can receive funding via the world's largest carbon pricing system, the EU ETS. In other words,

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EU policymakers consider carbon dioxide utilisation to be a key technology to contribute to climate change mitigation and to meet the Paris Agreement. Following the increased opportunities for funding, there is a steadily growing number of research articles and conferences and within these, expectations on carbon dioxide utilisation are taking form.

Carbon dioxide utilisation is currently at an early stage of development where it cannot compete on measures such as performance, price or design. It is still in an 'expectations phase' (van Lente and Bakker 2010) where the expectations on future performance and imagined solutions are the competing parameters. At this stage the expectations on carbon dioxide utilisation are being constructed within the techno-scientific domain and the concept has not yet gained enough attention to become part of a broader public discourse (Jones et al. 2017). In this article we therefore focus on the expectations circulating in articles published in scientific journals and conference proceedings. These articles are written by academics, company-based researchers, analysts at international organisations such as IEA, among others. This selection should therefore well represent the expectations that circulates on carbon dioxide utilisation among scientists. The analysis builds on sociology of expectations which states that expectations coordinate action and shape the path of technological development and thus defines the borders for what the new technological field contains and should be (Borup et al. 2006). What carbon dioxide utilisation should entail and what it is supposed to be able to do is still negotiated. The future design of the technology is based on what is now seen as an important functionality for the technology, important characteristics for it 'to count' (van Lente 2000; van Lente and Bakker 2010). Simpler put: what is promised now becomes a requirement later. For a proponent of an emerging technology such as carbon dioxide utilisation, it is thus important to argue for and against what kind of promises that can be made, to put a bar on the expectations, build networks and attract resources. These arguments are part of the process of constructing the concept 'carbon dioxide utilisation' and in this process a negotiation among conflicting expectations is taking place.

The aim of this article is to make conflicting expectations on carbon dioxide utilisation visible. Since the emerging technological concept is considered to be part of a low-carbon strategy, there is a need to articulate the implications of these conflicts for managing technology development. For example, the fundamental difference between the pronounced expectation on carbon dioxide utilisation to mitigate climate change and the co-existing aim to develop oil extraction methods inevitably creates conflicting expectations on the defining characteristics of what carbon dioxide utilisation 'essentially is'. The variety of ways in which the mitigation potential is articulated and assessed demonstrate that there is an ongoing formation of how this techno-scientific field should develop. What expectations get adopted and gain financial support will shape the future levels of greenhouse gas emissions in different directions. Making the conflicting expectations more visible is thus important from a societal perspective in order to distinguish the technological pathways of climate change mitigation strategies and oil extraction methods and make the different outcome of them clear to policy makers and research funders. Given the urgency to address climate change, the discussion and potential implementation of new technologies that claim a mitigation potential must be scrutinised thoroughly.

The article is organised as follows: after the introduction, the research approach is developed via a description of the theory that guides our analytical approach and material selection in section 2. The conflicting expectations found through an in-depth text analysis are presented in section 3, followed by a discussion on the outcome and its implications in section 4. Section 5 concludes the article.

2. Research approach

2.1. Sociology of expectations

Expectations are an important part of legitimising a new technology and its use in a socio-technical system. By envisioning a future in which the proposed technology plays a vital role, resources and support are attracted (Deuten and Rip 2000; Borup et al. 2006). The process of creating expectations and how it influences actor behaviour has been studied in sociology of expectations (Borup et al. 2006). The dynamics of expectations can be understood as a cyclic process where expectations are built through experimentation and advocacy activities which turn into promises and an accepted agenda for the technology (van Lente and Rip 1998).

The cyclic process often starts with the most fundamental part of expectations on a technology, namely the idea that a problem will be solved if the technology is implemented (Hultman and Nordlund 2013). The expectation to solve a particular problem, if the technology is developed and implemented, then becomes a promise. Such promises, when accepted as part of the technology, are turned into requirements for what the technology not only could but *should* be able to deliver (van Lente and Rip 1998; te Kulve et al. 2013). The requirements provide orientation for which characteristics the technology should have and where it should be applied. Expectations are thus turned into requirements that guide development and innovation activities (van Lente 2000). These expectations can refer to different 'levels' (van Lente and Bakker 2010). They can be *specific* and related to a local agenda and specific technical requirements, *functional* by making clear what contributions can be made to the technical-scientific field, or *generic* specifying to what societal agenda a contribution is made. While proponents for different technologies might contribute to the same expectations on the generic level, they can still compete for resources based on different expectations at the functional and specific level. In this way different proponents compete while they also support each other, developers of different technologies for carbon dioxide utilisation all want to attract general support for carbon dioxide utilisation while this general support also hinges on specific and functional expectations that the technologies will be able to deliver.

The generic expectations also influence the kinds of requirements that follow from functional and specific expectations. Budde and Konrad (2019) similarly argue that expectations on different levels support each other, if actors make these linkages. When a generic expectation becomes dominant, actors with conflicting views still have to relate to that expectation, either by aligning their own expectations or by disputing the dominant one (van Lente and Rip 1998). A process of alignment also tends to conceal involved uncertainties and potential conflicts (Konrad 2006). Carbon dioxide can be utilised for many different applications and technologies, varying from drop-in fuels to plastics and other carbon-based materials. Whereas different technological solutions to a certain application may compete, at this early stage through the means of expectations, the interest in this article lies rather with the conflicts that arise when linkages are created between generic expectations and different visions of future socio-technical systems and how these conflicts are expressed through the linkages between different levels of expectations.

2.2. Analytical process

In order to discern potential conflicts between expectations and how they are expressed we first mapped the expectations in our selected material in accordance to answers to the six questions below. These questions were formulated based on the insights from sociology of expectations presented above and helped us discern the relations between generic, functional and specific expectations, and how different requirements are related to these different levels of expectations and socio-technical visions.

(1) What is the problem that carbon dioxide utilisation promises to solve?
(2) Is this promise connected to a specific application?
(3) What requirements are presented in relation to a particular expectation?
(4) Which are the different applications of carbon dioxide utilisation presented and how are they related to each other – are they in a position of competition or compatibility?
(5) Who are the advocates of the different expectations?
(6) What kind of future socio-technical system is envisioned in relation to the expectations?

After the initial mapping, an in-depth text analysis of why and how carbon dioxide utilisation is being represented as a promising technology was made to identify conflicts and where in relation to the linkages between expectations and visions these conflicts emerge.

2.3. Material selection

The analysed material was selected from scientific journals that propose and assess different applications of carbon dioxide utilisation, and thereby express expectations. The material was derived from searches in Web of Science and ScienceDirect using diversified keywords to cover the most commonly used expressions and abbreviations for the concept of carbon dioxide utilisation: 'carbon (dioxide) utilis/zation', 'CDU', 'CO2 utilis/zation', 'carbon dioxide use/age', 'carbon capture (storage) and utilis/zation', 'CCU', 'CCSU', 'CCU&S' 'carbon (dioxide/capture and) reuse', 'CCR' and 'carbon (dioxide) recycling'. Out of the broad search, we selected only those articles that explicitly dealt with carbon dioxide utilisation. To confirm the outcome of the search, a separate scanning and cross-referencing was made which resulted in another 10 relevant articles added to the material.

In total 57 articles were selected and analysed in depth; these are listed in the supplementary material which can be found online. We did not select any specific timespan, but almost all the articles that have been selected were published after 2010 and just above half of them were published after 2015, see Table 1. This indicates a formation period for the expectations on carbon dioxide utilisation between 2010 and 2017, after which the technologies have received more attention and funding with a dominant expectation that the concept would contribute to reduced greenhouse gas emissions.

The authors of the selected research articles work dominantly in Western Europe and Asia, but it is a global scientific discussion with authors positioned on all continents except South America. All countries can be seen in Table 1. We found that the expectations where not connected to any specific geographical clusters, and therefore we have not given any further importance to the

Table 1. Overview of the spread of the material regarding publication year, nationalities, and the most common areas of research.

Country	No.	Publication year	No.	Top academic disciplines	No.
Australia	1	2006	2	Chemical Engineering	12
Austria	1	2007	0	Chemistry	10
Belgium	1	2008	1	Energy Engineering	10
Canada	1	2009	0	Material Science	7
China	6	2010	2	Catalysis Studies	7
Denmark	1	2011	6	Industrial Chemistry	6
Egypt	1	2012	3	Environmental Science and Engineering	4
Finland	1	2013	6		
France	5	2014	6		
Germany	7	2015	13		
Greece	1	2016	17		
Iran	2	2017	1		
Italy	9				
Japan	1				
Malaysia	2				
Nigeria	1				
Qatar	2				
Spain	3				
Switzerland	2				
Taiwan	1				
The Netherlands	3				
UK	8				
United Arab Emirates	1				
USA	7				

Please note that the affiliation of all authors is accounted, and since the number of authors vary between the publications, the number of countries does not correspond to the number of publications.

spread or geography of each article. Finally, the material is published with affiliations to a variety of academic disciplines, as can also be seen in Table 1. The most common discipline is chemistry, represented in the form of chemical engineering, chemistry, and industrial chemistry. Furthermore, catalytic studies, energy engineering and material science are among the most common areas of research. The remaining articles follow the same pattern and are published almost entirely within science or engineering. Besides the academic authors, about a dozen articles are published by authors affiliated to public agencies, research institutes, and private companies. They in turn work in the fields of energy, environment, petrochemistry, or manufacturing industry. This implies that even if there is diversity in the geographical spread, the formation of the expectations of carbon dioxide utilisation takes place dominantly within science and engineering, and especially in the field of chemistry.

3. The conflicting expectations on carbon dioxide utilisation

Our mapping shows that there is one dominant generic expectation: that carbon dioxide utilisation will contribute to climate change mitigation. This expectation has turned into a promise and constitute a fundamental identity for technologies and applications associated with carbon dioxide utilisation. That the promise to contribute to climate change mitigation is being widely accepted is indicated by the fact that in many articles it is not elaborated on *how* it will be able to contribute to reduced greenhouse gas emissions, it is simply stated as a fact in the introduction section or the abstract. This promise of reduced climate impact through the utilisation of carbon dioxide, is being supported, assessed, and questioned in relation to two different types of visions – separated by whether or not fossil fuels will be part of the socio-technical system in the future. Fossil fuels are not necessarily envisioned as a desirable part of the future but that they are unavoidably so. A general agreement in our selected material is that it is not likely that the demand for carbon will diminish anytime soon. Not only is it likely that we will use as much carbon-based materials and fuels in the future, but this use is an essential part of 'the current civilisations' and something that 'shape[s] our life style' (Song 2006, 7). This claim supports the importance of utilising carbon dioxide but depending on which kind of future is envisioned the *way in which* carbon dioxide is to be utilised will differ. The two different kinds of visions are aligned to conflicting specific and functional expectations which becomes visible within three different themes: how carbon dioxide utilisation technologies shall be assessed, how carbon dioxide utilisation should be framed, and which applications are suitable for carbon dioxide utilisation.

3.1. Requirements on the source of carbon dioxide and energy input

Requirements on which production route and feedstock source that proponents of carbon dioxide utilisation express cannot be explained solely by linkages to the expectation that it will contribute to climate change mitigation. In most of the applications for carbon dioxide utilisation, captured carbon dioxide is converted into hydrocarbons, a process which require hydrogen. Carbon dioxide can be captured from flue gases in power plants, from bio-based processes or directly from ambient air. Hydrogen is presently mainly produced through natural gas reforming, but electrolysis can be used as well. The latter process requires large amounts of electricity and is the most energy consuming part of producing hydrocarbons from carbon dioxide (von der Assen et al. 2015). The requirements therefore rather reflect the different ways in which the future energy system is envisioned. When the energy system is envisioned not to deviate much from the present fossil-dominated one, capturing carbon dioxide from ambient air is dismissed as the worst option from a climate mitigation point of view, since more energy is required compared to the more concentrated sources, such as coal-fired power plants, steelworks or biofuels production. When the energy system is envisioned to be based mainly on renewable energy sources, air capture is assessed as a good option to enable so called 'closed-loop carbon-neutral' cycles (Graves et al. 2011, 1).

Using carbon dioxide from fossil sources is expected to improve the environmental performance of the fossil industry, while creating end products, such as fuels, that in turn contribute to the development of a more sustainable energy system. It is also argued, or implicitly assumed, that if carbon dioxide from fossil sources is to be used for climate change mitigation, this creates requirements on the input. The most common requirement on input is that hydrogen must be produced using renewable energy: 'The conversion of CO_2 to chemicals and energy products … requires hydrogen that is generated from renewable energy resources' (ElMekawy et al. 2016, 359–360).

Advocates for using renewable carbon dioxide argue that in order for the end product to be sustainable, all input must be fossil-free: 'To allow a stabilisation of its atmospheric concentration, the CO_2 used in such a strategy must be of non-fossil origin' (Meylan, Moreau, and Erkman 2016, 367). This renewable carbon dioxide could be captured from ambient air or originate from biomass. Carbon dioxide from biomass is viewed as a complementary source of carbon for plastics and fuels with new models of so-called 'biofactories' or 'electro-biorefineries' (Abate et al. 2015, 2855; ElMekawy et al. 2016, 357). Carbon dioxide utilisation is not necessarily presented as a superior option to biomass, instead a vision of improved biorefineries takes shape, where carbon dioxide provides an opportunity to increase the yield of biomass, by using a larger part of the biogenic carbon which would otherwise be 'lost' as emissions. Utilising carbon dioxide is then linked to a vision of an energy system with only renewable energy sources, without the sustainability issues connected to biomass utilisation. This is then envisioned as the only long-term sustainable option: a chemical, plastics and fuels industry without fossil fuels, sometimes with artificial photosynthesis as the final goal. 'One can think of this scenario as a straightforward extension of the hydrogen economy to include carbon, as a direct chemical analog to the photosynthetic creation of biomass, or even as reversing combustion' (Stechel and Miller 2013, 34) (Figure 1).

3.2. Framing and symbolism

The most frequent way of naming the concept of carbon dioxide utilisation is the abbreviation CCU (Carbon Capture and Utilisation). This name focuses on *utilisation* over *storage* and is used to contrast and link carbon dioxide utilisation to CCS (Carbon Capture and Storage). When highlighting the complementarity between CCS technologies and carbon dioxide utilisation, the combination of utilisation and storage is presented as an opportunity, since utilisation of carbon dioxide can be a way of creating legitimacy for CCS and makes a continued use of fossil fuels possible. As the carbon dioxide is given economic value, economic incentives for capture technologies can be created. Utilising carbon dioxide is then part of the same concept as CCS and they can develop in parallel, as 'siblings' (North and Styring 2015, 493). Variations of the abbreviation CCUS (Carbon Capture Utilisation and Storage) is used to describe that the concept includes capture, followed by utilisation *or* storage. Typically, CCUS advocates argue that carbon dioxide should be captured from large (fossil) industrial plants, to be either converted into desired applications or stored in geological formations. It is suggested that CCU should be included in a common carbon dioxide technology roadmap together with CCS as a way to overcome some of the obstacles associated to CCS, such as public perception, transportation or cost (Cheah et al. 2016; Barbarossa et al. 2014). Using carbon dioxide is also argued to be a better way to reduce emissions than sequestering the carbon (CCS), because 'carbon capture

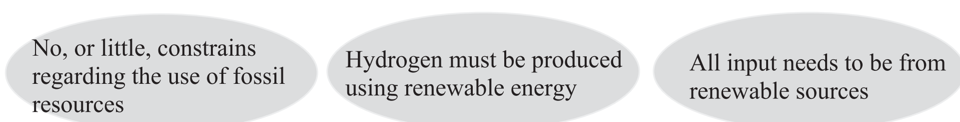

Figure 1. Three conflicting requirements on the input of energy, carbon dioxide and hydrogen for carbon dioxide utilisation. The different requirements are likely to have different potential to contribute to climate change mitigation.

and storage faces problems including leakage, risks to the environment, and considerable costs and energy requirement' (Reiter and Lindorfer 2015, 40).

Proponents that envision the future to be fossil free, instead refer to carbon dioxide utilisation using other abbreviations, such as CDU (Carbon Dioxide Utilisation). CDU is used to shift the focus from *capture* towards *utilisation* and this is often done in order to deliberately dissociate the concept from CCS, and the negative aspects associated to it. Other advocates highlight the circularity of the concept, by naming it CCR (Carbon Capture and Recycling), 'CO_2 upcycling' or 'CO_2 reuse'. Three recurring symbolic representations have been identified in the material: (i) circularity (or closed loops), (ii) naturalness, and (iii) accessibility. These concepts are often combined and used interchangeably, and what they adhere to is not always consistently followed throughout the text; specific abbreviations or key words are often mixed with other defining features. These assertions of recyclability, flexibility and availability feed expectations that nothing needs to be lost or sacrificed. Continued use of plastics, fuels and other materials is possible without the association to fossil fuels. What these framings and suggested names have in common is the urge to separate the concepts of utilisation from storage: '*CCU*, unlike CCS, may allow for a *closed loop recycling* system' (Fraga and Ng 2015, 310, emphasis added). The idea of circularity is modelled on the carbon cycle and it is proposed that by implementing carbon dioxide utilisation on a large scale, a 'new anthropic carbon cycle' would be introduced (Peters et al. 2011; Zangeneh, Sahebdelfar, and Ravanchi 2011). This cycle would be powered by solar energy, in which hydrocarbons are 'recycled' through 'reverse fuel combustion' (Graves et al. 2011). The idea of a closed loop is induced through frequent use of figures and images, showing circular flows or arrows or explicitly comparing the proposed concept with one in which the flows are not closed in a loop. The contrast between utilising carbon dioxide and carbon from fossil fuels is illustrated by showing how the atmosphere is now part of the loop, rather than the lithosphere (Graves et al. 2011; Meylan, Moreau, and Erkman 2016). Carbon dioxide is illustrated as 'extracted' from the atmosphere and then '*re*-emitted' when fuels are combusted (Meylan, Moreau, and Erkman 2016: fig. 2).

In claiming the naturalness of carbon dioxide utilisation, analogies to photosynthesis are frequently used. This way of imitating nature, using the sun as (endless) energy provider will ensure us a safe way to continue using chemicals, materials and fuels. Combined with biomass and biotechnologies, carbon dioxide utilisation thus enables the creation of 'solar fuels' (Meylan, Moreau, and Erkman 2016, 103), through the use of 'artificial photosynthesis' (Abate et al. 2015, 2854) and improved biorefineries (Cheah et al. 2016; Aresta, Quaranta, and Tommasi 1992). Stechel and Miller (2013) expand on this notion by claiming that fossil fuels are in fact 'stored sunlight' and carbon dioxide utilisation will provide the same service but in a radically shorter time span.

But there are also other reasons why some proponents of carbon dioxide utilisation do not want to associate it with CCS. It is argued that there is a danger to promise that carbon dioxide utilisation will reduce greenhouse gas emissions, since it overshadows other 'multiple benefits which include the economic, social and environmental benefits of CCU' (Li et al. 2016, 288). In two of the articles it is claimed that if carbon dioxide utilisation is to succeed, the mitigation hype needs to be dropped, and that focus should be shifted to the other benefits since 'a commingling of CCU and CCS fuels misunderstandings or false expectations that can be counterproductive for the further development of CCU' (Bruhn, Naims, and Olfe-Kräutlein 2016, 38).

3.3. Expectations on suitable applications for carbon dioxide utilisation

The promise that carbon dioxide utilisation contribute to climate change mitigation is associated with conflicting expectations on suitable applications. Advocates of different end-products use the same arguments but end up in different conclusions. There are conflicting views on what characteristics are most suitable for the promoted applications – is the highest, and most effective, mitigation achieved through the potential of large market volumes, long-term storage or economic viability? Suitable criteria for assessing which applications should be preferred, and which solutions should be dropped, are sought, but there is no consensus on how that should be done. This is partly due to the difference in envisioned transition periods in which carbon dioxide utilisation should be implemented. Here we see a tension between highlighting the benefits of carbon dioxide utilisation being compatible with the current fossil energy system and proposing its transformative potentials for a future without fossil fuels.

In terms of reducing emissions, the production of fuels or chemicals are debated, as to which is the best option. The magnitude of the market size for fuels is argued to be an advantage because using large amounts of carbon dioxide would significantly contribute to emissions reduction. 'In fact, the only potential product family that could consume CO_2 feedstock at a level commensurate with current emissions is hydrocarbon fuels … ' (Stechel and Miller 2013, 30). The counterargument used for producing chemicals over fuels is that materials such as plastics and concrete have a longer lifetime, and therefore a higher long-term mitigation potential. The smaller market size is not an issue, it is argued, because of the longer fixation period, a factor that is argued to be 'decisive for climate protection' (Markewitz et al. 2012, 7302).

Another contested application is enhanced oil recovery, a technology used to increase the extraction of crude oil from oil fields. The advocates argue that the greenhouse gas emissions should be considered the problem, not the fossil fuels that are the source of the emission. Captured carbon dioxide is proposed to replace methane in enhanced oil recovery with benefits for the climate and the surrounding environment, thus creating sustainability incentives for the application. If carbon dioxide is used instead of methane, a second benefit is that the 'relatively clean' (Al-Saleh et al. 2012, 105) fuel methane can be used in other parts of the national energy system. On the contrary, others argue that enhanced oil recovery is inherently bad for the climate, as the purpose is to extract more fossil resources. This application should therefore not be considered as carbon dioxide utilisation, since 'enhanced oil recovery (and other nonconventional fossil fuels) cannot be part of efforts to reduce atmospheric carbon dioxide levels or develop a sustainable economy' (North and Styring 2015, 500).

4. Conflicting expectations – a balance act that will be hard to keep up

Carbon dioxide utilisation promises that a continued reliance on fuels and materials with a carbon content is possible while mitigating climate change. Our analysis shows that this promise gives rise to conflicting expectations on several levels. The early idea of using carbon dioxide from fossil flue gas as a means to mitigate climate change, continues to set the scene for the present expectations. On a generic level the mitigation expectation is accepted, but questions contesting it are starting to sprout: Can carbon dioxide utilisation really mitigate climate change? And is this necessary for it to be an interesting technological concept? This problematisation itself confirms that this expectation has become a dominant part of the technological concept (van Lente and Rip 1998). Furthermore, conflicting functional and specific expectations arise regarding feedstock requirements, framing of the concept and applications.

The generic expectation to mitigate climate change is being related to two conflicting visions. In nearly half of the articles it is suggested that carbon dioxide utilisation can be used to legitimise continued extraction and use of fossil fuels by using carbon dioxide in for example enhanced oil recovery or to capture greenhouse gas emissions from fossil-fuelled power plants or transport. Others claim that carbon dioxide utilisation is part of a future beyond the fossil fuel era, focusing on closed loops and solar energy as basic driving forces of economic and technological development. Carbon dioxide-based hydrocarbon applications such as plastics and fuels, produced via entirely renewable input, are then envisioned to be part of a future circular economy.

The conflicts between expectations made visible in our study are not necessarily recognised by any of the authors or in the wider research community. Some of the expectations are being actively debated, as shown in the analysis, but other statements are more ambiguous. However, clear disagreements between authors and ideas are seldom the case, conflicting functional and specific expectations can even be found within the same text where an author can argue for two ideas that are somewhat contradictory. This is not unusual for advocates of emerging technological concepts where the purpose of a text is not necessarily to define or delimit the concept, but rather to build networks and attract resources (van Lente and Rip 1998).

While competing applications and conflicts between the visions and expectations do not necessarily inhibit the support for and development of carbon dioxide utilisation technologies, financial support and implementation of these conflicting expectations may lead to different future emissions of greenhouse gases. To avoid creating futures in which fossil fuels are prominent, governing actors should pay attention to how shifting expectations on carbon dioxide utilisation technologies might follow from shifts in envisioned energy systems rather than changes in technological performance or suitability. Budde and Konrad (2019) show in a similar study that expectations alone are not able to engage support but when they are linked to visions and expectations about the future energy system, they receive attention. Furthermore, policy actors have been criticised to shift their attention and resources too quickly, following the most promising expectations (and disappointments) too closely, and thereby failing to provide long-term policies (Melton, Axsen, and Sperling 2016). A reflexive governance with the aim of meeting the goals of the Paris agreement should therefore not only focus on how to manage and support carbon dioxide utilisation but also which kind of visions they allude to.

In order to avoid potential policy failures, we suggest, in line with Bakker and Budde (2012), that evaluation criteria are important in a selection process, otherwise the risk is that research funding aimed at low-carbon technologies result in increased emissions of carbon dioxide. These evaluation criteria should pay particular attention to the kind of potential lock-ins an adoption of carbon dioxide utilisation technologies could lead to. Requirements on inputs, such as energy, the source of carbon dioxide, and hydrogen production, as well as the potential of the applications should be scrutinised in conjuncture with the kind of future socio-technical system in which these technologies are envisioned. This does not mean that carbon dioxide utilisation technologies are *not* interesting if they cannot live up to the promise of climate change mitigation but that there is an inherent danger in supporting lock-in if they are dependent on the fossil fuel industry to be able to operate.

5. Conclusions

Our analysis shows that some of the conflicting expectations on carbon dioxide utilisation cannot (easily) coexist and are likely to continue to be contested. These conflicting expectations mainly result from different time-frames and envisioned futures in which carbon dioxide utilisation should take place. Framing of carbon dioxide utilisation is thus important and a key factor is whether or not it should be associated with CCS. In some cases, the distinction between what is storage and what is utilisation is not even agreed upon. Another conflict concerns whether or not carbon dioxide from fossil sources should be 'allowed' for carbon dioxide utilisation to be able to deliver on its promises – to ensure a continued use of carbon rich products such as plastics and fuels, while mitigating climate change.

Conflicting expectations are important to pay attention to in deliberations on how, and if, to support new technologies. The analysed expectations envision a wide range of energy systems that include many potential solutions and applications, something which is common for emerging technologies. However, given the urgency to take action on climate change, the expectations on a technology that promises climate change mitigation is even more important to scrutinise. The conflicting expectations exposed by the analysis illustrate that different possibilities for action are created, and if enacted they will shape the future of carbon dioxide utilisation and its inherent greenhouse gas emissions in different directions.

Which of the conflicting expectations that will be most prominent in the further development of carbon dioxide utilisation technologies, and their effect on innovation activities and policy, require further analysis. Nevertheless, the continued framing of carbon dioxide utilisation and how it relates to other similar concepts matters for its potential to attract support and attention. Should carbon dioxide utilisation be considered to be part of a bio-strategy, a renewable energy system or a sibling to fossil-related solutions such as CCS? Trying to accommodate these different framings in one generic expectation might be a strength at this early stage, because it creates room for interpretive flexibility of and wider support of the concept carbon dioxide utilisation. On a longer term, however, it is likely that such a balance act will be hard to keep up because of the incompatibility between strategies supporting a transition away from fossil fuels and strategies that simply tries to make fossil fuels 'greener'.

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