# Blending Acceptance as Additional Evaluation Parameter into Carbon Capture and Utilization Life-Cycle Analyses

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Abstract: Carbon Capture and Utilization (CCU) captures and uses $CO_2$ as a feedstock to produce carbon-based saleable products. However, sustainable technology innovations are only attractive to investors and justify (public) subsidies if they provide economical or ecological added value. Therefore, life-cycle analyses (LCA) are applied to identify the environmentally most optimal option of a technology scenario. Since LCA do not address the social dimension of sustainable innovations so far, a study is presented, where acceptance is assessed as additional life-cycle evaluation parameter. A prestudy (qualitative interviews, n = 25 participants) was run to identify acceptance-relevant parameters of CCU site deployment. In a conjoint study (n = 110), which investigated the acceptance of CCU site deployment scenarios, the profitability, $CO_2$-source, and type of $CO_2$-derived product were systematically varied as acceptance-relevant criteria. Findings show, that profitability had the highest impact on CCU technology scenario preferences. Fuel was the most attractive CCU product option and steel plants were the most preferred $CO_2$-source. In sensitivity analyses specific acceptable and nonacceptable CCU technology scenarios were identified. The assessment of acceptance for CCU deployment scenario parameters allows to include acceptance as additional evaluation and weighting parameter into life-cycle analyses of CCU technology scenarios.



## 1 INTRODUCTION

Fighting climate change caused by greenhouse gas emissions is one of the greatest worldwide challenges today. Carbon capture and utilization (CCU) represents a range of technologies, developed to reduce $CO_2$ emissions and fossil resource use by capturing, "recycling", and using $CO_2$ as a feedstock to produce carbon-based saleable products. Most CCU technology applications still have low technology readiness levels (Wilson et al., 2015), but first $CO_2$-derived products are now reaching the end-consumer market. Apart from the technical feasibility of CCU, the technology must provide added ecological and economic value and – most important for its long-term success – reach public acceptance. So far, the public perception of CCU is an under-researched field (Jones et al., 2017), which also applies to the consideration of acceptance in the design and evaluation of CCU technology deployment scenarios.

### 1.1 Carbon Capture and Utilization

Carbon Capture and Utilization (CCU) has gained attention as climate change mitigation technology in recent years, since it has the potential to limit or reduce atmospheric releases of $CO_2$ and to replace fossil resource use (Markewitz et al., 2012). CCU refers to a broad range of eco-innovative and sustainable technologies, which use $CO_2$ as a feedstock for the production of diverse carbon-derived products (Styring et al., 2015). Different CCU production routes and resulting product types have been developed: direct or physical utilization, biological, and chemical utilization. In direct or physical utilization, $CO_2$ is used as refrigerant, as extinguishing agent or in cleaning processes. The captured $CO_2$ can also be transformed via biological processes into fuels or bio-oils. The chemical utilization route of $CO_2$ allows the production of urea, methanol, cyclic carbonates, salicylic acid, or polyol (Markewitz et al., 2012). Here, $CO_2$ can be stored partly permanent (e.g., in liquid fuels) or even for



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long-term time periods (e.g., in polymers or cement). The production of plastic substances such as polyol, polypropylene, and polyurethane based on carbonates and polycarbonates allows access to the very high demand and sales volumes in the plastics sector (Coates and Moore, 2004). The chemical utilization route of CCU is highly promising due to the high availability of $CO_2$, savings of fossil resources in the production of plastic products, and a broad spectrum of plastic product variants (Markewitz et al., 2012). Thus, from a technical perspective, CCU has great ecological and economic advantages: by emitting less $CO_2$, CCU can contribute to climate change mitigation targets and the use, costs, and dependency on expensive and limited fossil resources can be reduced. However, "green" and sustainable technology innovations such as CCU are only attractive to investors and justify (public) subsidies if they provide economical or ecological added value. In the past, techno-economic assessments were most commonly employed to identify the most cost effective option. Currently, life-cycle assessments (LCA) are increasingly used to identify the environmentally most (or least) benign option of a technology scenario.

## 1.2 Life-Cycle Assessment of Carbon Capture and Utilization

"Green" technology innovations such as Carbon Capture and Utilization require methods and tools to assess and compare the environmental impact of their products or services to the society. One specific evaluation framework is the Life-Cycle Assessment (LCA) (Rebitzer et al., 2004), which estimates and assesses the environmental impacts attributable to the life-cycle of a product in the form of environmental impact measures such as climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, toxicological stress on human health, and ecosystems, etc. In LCA, energy and materials used and wastes released to the environment are identified and evaluated regarding opportunities to affect environmental improvements (Rebitzer et al., 2004).

In the context of CCU, several life-cycle assessments were conducted, which either focused on the comparison of specific CCU process routes with conventional process routes (e.g., von der Assen et al., 2013) or the comparison of different CCU technology process steps (e.g., von der Assen et al., 2014). A study on life-cycle assessment of $CO_2$-utilization for polyurethane concluded that even though chemical $CO_2$-utilization does not lead to a significant reduction in the global emissions budget, significant amounts of fossil resources (mostly oil) and $CO_2$ emissions resulting from the production can be saved compared to the manufacture of conventional products (von der Assen and Bardow, 2014). Not restricted to the field of CCU, but also for other eco-innovations, "hot spots" and their impact on the profitability and competitiveness of the technology compared to conventional routes were analysed (Castellani et al., 2017).

Even though LCA are referred to as holistic approaches due to their broad evaluation perspective from "cradle to grave" of a product, sustainable innovations do not only exert environmental, but also social impacts. So far, LCA do not address the social dimensions of sustainable innovations, even though the perception and acceptance of a technology, product or service by the public can finally decide about the success or failure of a technical innovation (Batel et al., 2013). Public acceptance refers to a positive reception or behavioral response (support) to a technology. In contrast, missing acceptance can result in protesting actions against the technology infrastructure or avoidance of purchasing and using the technology and its products (e.g., Wallquist et al., 2012).

The present paper, therefore, aims for an investigation of social indicators such as perception and acceptance of the CCU technology in a LCA-framework. Before the research approach is detailed in section 2, the following section 1.3 focuses on the state-of-the-art regarding the public perception and acceptance of CCU.

## 1.3 Public Perception and Acceptance of Carbon Capture and Utilization

Due to the young age of the CCU technology and the comparably small number of mature carbon-based products on the market (e.g., mattresses (Covestro, 2016); or synthetic methane (Audi, n.d.)), empirical research about the perception and acceptance of CCU is just emerging in the last years. These studies mainly focus on the socio-political level of acceptance (i.e., the acceptance of technologies by major the general public, policy makers, and other key stakeholders) as well as on market acceptance (i.e., the acceptance of carbon-derived products by potential consumers) (Wüstenhagen et al., 2007). Most empirical studies on the perception and acceptance of CCU were based on qualitative methods, trying to identify underlying motives and determinants of CCU acceptance (e.g., Jones et al., 2016; Jones, 2015; van Heek et al., 2017), but first quantitative studies directed on a quantification of CCU acceptance levels (Perdan et al., 2017), modeling CCU perception and acceptance (Arning et al., 2017) or the decision process (van Heek et al., 2017b) can be found today. These studies show, that the general awareness and information level about the CCU technology and carbon-derived products is rather low in the general public (Perdan et al., 2017). Even though CCU is generally positively perceived due to its environmental benefits, especially technical lay-people with a low awareness of CCU associate higher risks with this technology. Frequently stated risks or concerns in the context of CCU refer to health risks (e.g., fear of headaches or suffocation due to $CO_2$-leakage from CCU products), environmental risks (e.g., fear of pollution during the production process or during product disposal), product quality risks (e.g., lower durability) or sustainability risks (no long-term solution, when $CO_2$ is released after product disposal) (Arning et al., 2017).

Summing up, empirical acceptance research on CCU technology and products shows, that the acceptance of a green technology innovation by the public should not be taken for granted. To develop technology scenarios, which are not only economically and ecologically feasible and effective, but also acceptable from the public or consumer side, the present paper is directed on an integration of two methodological approaches: life-cycle analyses and empirical acceptance research. For the first time – to best of our knowledge – acceptance parameter input is assessed in a life-cycle scenario and is regarded as additional life-cycle evaluation parameter. By blending acceptance into life-cycle assessments, technical innovations have a higher chance to evolve into social innovations that meet people's requirements and expectations and yield less risk of failure due to public opposition.

Therefore, the present study pursued the following *research aims*:

1. Identifying acceptance-relevant criteria for a CCU life-cycle scenario directed on the deployment of a CCU site
2. Measuring acceptance of CCU site deployment criteria and different CCU deployment scenarios
3. Complementing technical and environmental evaluation parameters of existing life-cycle assessment approaches by acceptance parameters

# 2 METHODOLOGY

In the following section, the methodological approach of the study is detailed, i.e., the conjoint analysis procedure, the prestudy, and the sample.

## 2.1 Conjoint Analysis

Conjoint analysis (CA) methods combine a measurement model with a statistical estimation algorithm (Rao, 2014). Compared to survey-based acceptance studies, which are still the dominating research method in information systems and acceptance research, CA allow for a holistic and ecologically more valid investigation of decision scenarios (Alriksson and Öberg, 2008). Specific product profiles or scenarios are evaluated by respondents, which are composed of multiple attributes and differ from each other in the attribute levels. CA deliver information about which attribute influences respondents' choice the most and which level of an attribute is preferred. Preference judgments and resulting preference shares are interpreted as indicator of acceptance (Arning et al., 2014). In the present study, a choice-based-conjoint (CBC) analysis approach was chosen, because it closely mimics complex decision processes, where more than one attribute affects the final decision (Rao, 2014).

## 2.2 Selection of Attributes

A qualitative interview prestudy was conducted to identify acceptance-relevant attributes and levels in the context of CCU deployment to be used in the conjoint analysis. Note, that the CCU life-cycle was not operationalized from a technical perspective, but from a social science perspective, taking only acceptance-relevant factors of CCU deployment into account. To identify these acceptance-relevant factors, five focus-group discussions with n = 25 participants were conducted. Here, people with differing technical expertise, environmental awareness, age, and gender discussed perceived benefits, barriers, and deployment requirements from the publics' perspective. All interviews were recorded, transcribed, and analyzed by qualitative content-analysis. The following attributes and levels were extracted as being acceptance-relevant for CCU technology deployment:

1. *$CO_2$-source* with three levels a) chemical plant, b) steel plant, and c) coal-fired plant. The three point sources were chosen, because even lay-participants were familiar with them

and first pilot- or demonstration sites are already running in Germany.

2. *Profitability* of the CCU site with three levels a) no public financing necessary, b) start-up public financing for building the site, c) long-term public financing necessary.
   The aspect of profitability was emphasized by experts, thereby differentiating between the different production routes and types of $CO_2$-derived products (e.g., production of plastic products versus production of fuel).
3. *$CO_2$-derived product* with four levels a) mattress, b) fertilizer, c) fuel, d) drugs.
   Four different types of $CO_2$-derived products were chosen to represent the broad variety of potential products, which can be produced based on the CCU technology.

Because a combination of all corresponding levels would have led to 36 (3 × 3 × 4) possible combinations to evaluate, the number of stimuli was reduced. Each respondent was presented with only 12 random tasks, i.e., some levels of attributes did not appear together in one set. Therefore, a test of design efficiency was applied to examine whether the design was comparable to the hypothetical orthogonal design (Sawtooth Software, 2013). Design efficiency was confirmed with a median efficiency of 99% relative to a hypothetical orthogonal design.

## 2.3 The Questionnaire

SSI Web Software was used for questionnaire design. The questionnaire consisted of three parts: First, participants received an introduction into basic terms, functioning, and purpose of the CCU technology. They were also introduced into the decision scenario. To ensure that participants correctly understood all attributes and levels, all of them were defined and comprehensively described in the introduction. Second, participants answered the 12 conjoint choice tasks. They were asked to decide under which conditions they would accept the roll-out of the CCU technology. An example for a choice task is shown in Figure 1. The third part of the questionnaire consisted of general CCU acceptance items, assessing CCU as “beneficial”, “useful”, “risky”, and “threatening”, local CCU site deployment acceptance (all assessed on 6-point Likert-scales (1 = “do not agree at all” to 6 = “fully agree”)) as well as demographic data (age, gender, and education) and the general awareness and knowledge level about the CCU technology in specific (assessed on Likert-scales from 1 = “very low” to 6 = “very high”).

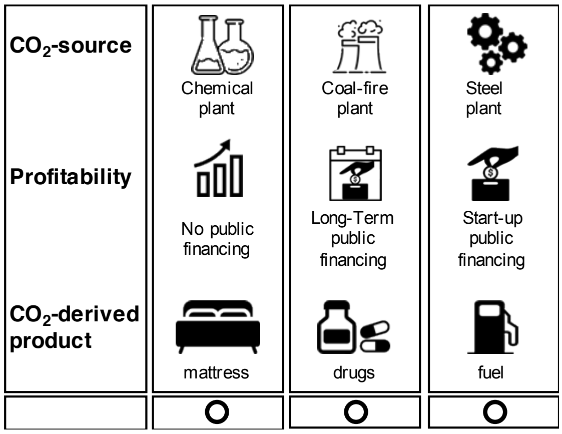


Figure 1: Example of a choice task in the CBC study. Respondents were asked to indicate the most preferred CCU deployment scenario.

## 2.4 The Sample

Data of n = 110 participants was analyzed (only complete data sets were included into the analysis), with 53.6% male and 46.4% female respondents. The mean age was M = 28.5 years (SD = 8.8), ranging from 17-59 years. The sample was highly educated with 60 respondents holding an university degree and 50 respondents holding a school leaving certificate.

The awareness and information level about the CCU technology was very low in the sample. The majority reported to have very low (69.1%) or low (17.3%) knowledge about CCU, whereas only 4.5% reported to have a good or very good (1.8%) knowledge about the CCU technology.

## 2.5 Data Analysis

Data analysis of conjoint data was carried out by using Sawtooth Software (SSI Web, HB, SMRT) (Sawtooth Software, 2013). Part-worth utilities were calculated based on Hierarchical Bayes (HB) estimation and part-worth utilities importance scores were derived. They provide a measure of how important the attribute is relative to all other attributes. Part-worth utilities are interval-scaled data, which are scaled to an arbitrary additive constant within each attribute, i.e., it is not possible to compare utility values between different attributes. By using zero-centred differential part-worth utilities, which are scaled to sum to zero within each attribute, it is possible to compare differences between attribute levels. Sensitivity or scenario simulations where carried out by using the Sawtooth market simulator. Likert ratings in the questionnaire were analysed descriptively (M, SD). Ratings > 3.5 were interpreted as approving, ratings < 3.5 as rejecting evaluation.

# 3 RESULTS

In this section, the findings regarding the acceptance of CCU site deployment are presented as well as the conjoint data analysis findings, i.e., relative importance scores for the three attributes, part-worth utility estimation findings for the respective attribute levels, and the simulation of preferences for different CCU site deployment scenarios.

## 3.1 CCU Deployment Acceptance

The general *perception of the CCU technology* was positive (M = 4.3, SD = 0.8). A minority (10.8%) of respondents evaluated the CCU technology as nonacceptable, whereas 78% perceived CCU as positive or highly positive (11.2%). Respondents evaluated CCU as beneficial (M = 4.3, SD = 1.0), useful (M = 4.4, SD = 0.9), not being risky (M = 2.9, SD = 0.9) or threating (M = 2.5, SD = 0.9).

Asked for *local acceptance* of CCU site deployment, 11% would react with protest, 56.4% would tolerate the site, and 16.4% would approve the deployment of a CCU site in their neighbourhood.

## 3.2 Relative Importance Scores

To evaluate the main impact factors on preferences for CCU deployment scenarios, the share of preference was calculated by applying Hierarchical Bayes Analyses. The relative importance scores of the attributes examined in the present study are presented in Figure 2.

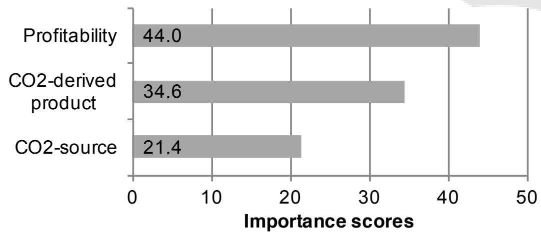


Figure 2: Importance scores for CCU deployment attributes in the CBC study.

The attribute "profitability" had the highest importance score (44.0%, SD = 18.0), followed by "$CO_2$-derived products" (34.6%, SD = 15.3) and "$CO_2$-source" (21.4%, SD = 14.8). The results indicate that the profitability of CCU site was the most dominant attribute to influence CCU deployment scenario acceptance. The type of $CO_2$-derived product was also important, but to a lesser extent. Interestingly, the $CO_2$-source was the least important attribute affecting CCU deployment scenario acceptance.

## 3.3 Part-worth Utility Estimation

The average zero-centred differential part-worth utilities for all attribute levels are shown in Figure 3. The attribute "profitability" displayed the highest range between part-worth utilities, which caused the high importance scores (see 3.1).

Focusing on absolute utility values of the attribute "*profitability*", the level "no public financing" was highly preferred, as indicated by the highest utility value (53.2, SD = 40.7). "Start-up public financing" was also accepted (utility = 12.8, SD = 18.4), whereas "long-term public financing" (-66.0, SD = 35.1) received the lowest utility value and was rejected by respondents.

Looking at *$CO_2$-derived products*, the most preferred product type was "fuel" (utility = 19.2, SD = 48.2), followed by "drugs" (utility = 9.5, SD = 48.8), which were also positively evaluated. Using $CO_2$ to produce fertilizer was evaluated neutrally (utility = 0.0, SD = 36.0). The only product, which received negative evaluations was the mattress consisting of $CO_2$ foam (utility = -28.6, SD = 26.6).

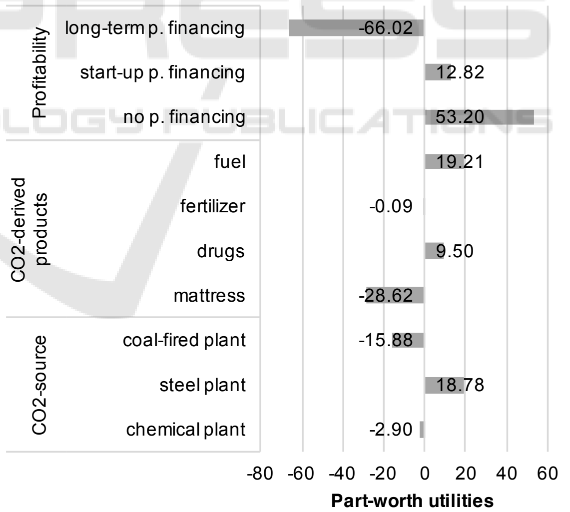


Figure 3: Part-worth utilities (zero-centred diffs) for CCU deployment attributes and levels in the CBC-study.

Regarding the *$CO_2$-source,* the most preferred point source was the "steel plant" (utility = 18.8, SD = 0.7). The other two $CO_2$-sources, the "chemical plant" (utility = -2.9, SD = 23.6) and - to an even higher extent – the "coal-fired plant" (utility = -15.9, SD = 34.1) were rejected in a CCU deployment scenario.

### 3.4 Preference Simulations for CCU Deployment Scenarios

In a next step, sensitivity simulations were carried out by using the Sawtooth market simulator. In the simulations, we investigated preferences for specific CCU deployment scenarios. Based on the preference patterns we identified in section 3.3, we simulated public preferences for a "best case" scenario and for four different CCU deployment scenarios.

The "best case CCU deployment scenario" with a steel plant as $CO_2$-source, fuel as $CO_2$-derived product, and no required public financing was accepted by 77.4% (SE = 2.8%) of respondents. A lower profitability in the beginning, which requires a start-up public financing led to only marginally reduced acceptance rates (77.2%, SE = 2.8%). In case of public long-term financing, the acceptance rates declined to 55.8% (SE = 3.2%).

In addition to the "best case"-scenario, four realistic and technically feasible scenarios were simulated.

- Scenario 1 – "Dream factory": This scenario was based on the "Dream factory" project of Bayer (Bayer Material Science, n.d.), producing $CO_2$-derived mattresses with $CO_2$ from a coal-fired power plant. It was characterized by a coal-fired plant as $CO_2$-source, a mattress as $CO_2$-derived product and was running profitable (i.e., no public financing necessary).
- Scenario 2 – "Mattress factory / chemical industry": This scenario resembled scenario 1 regarding the product (a mattress) and the profitability, only differing regarding the chosen (but also feasible) $CO_2$-source, which was a chemical plant.
- Scenario 3 – "Fuel production": The fuel production scenario was composed of a coal-fired plant as $CO_2$-source manufacturing fuel as $CO_2$-derived product. The fuel production site in this scenario requires public subsidies due to high energy costs in the production of hydrogen, which is not cost-effective, so far.
- Scenario 4 – "Fertilizer production": The fourth scenario refers to the physical use of $CO_2$ to produce fertilizers by chemical industry, which provides the $CO_2$-source in this scenario. No decomposition of molecules is necessary for the use of $CO_2$ in fertilizers. Thus, a profitable operation of a $CO_2$-derived fertilizer production site is feasible.

Figure 4 displays the results of the preference simulation of the four scenarios.

The best-rated scenario in our simulation was scenario 4 ("Fertilizer production"). This scenario was preferred by 47.7% of all respondents. Less acceptable (19%) was scenario 1 ("Dream factory"), which corresponds to a production site of foam mattresses in Germany.

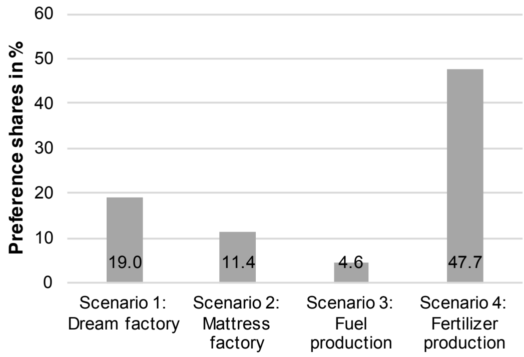


Figure 4: Preference simulation for CCU deployment scenarios.

Scenario 2, which resembled Scenario 1, except taking a chemical plant as $CO_2$-point source was preferred by 11.4%. The least preferred scenario was scenario 3 (4.5%), which contained a fuel production site subsidized with public funds and a coal-fired plant as $CO_2$-source. All four scenarios were rejected by 17.5% of participants.

Summing up the findings of the conjoint analysis, the profitability of the CCU site was the most acceptance-relevant criterion. Regarding the preferences for specific CCU technology and product parameters, respondents mostly preferred fuel as $CO_2$-derived product variant and steel plants as $CO_2$ point source. In the scenario analysis, the most preferred scenario was the cost-effective production of fertilizer, the least preferred scenario was the subsidised production of fuel.

## 4 DISCUSSION

Social indicators such as public perception and acceptance of technologies and products are not considered as evaluation parameters in LCA so far, even though they might exert considerable impact on the successful adoption of a technology. The present study was, therefore, a first attempt to address and include the social dimension of sustainable eco-innovations in life-cycle analyses. Based on a multi-level empirical approach, acceptance-relevant criteria of CCU site deployment were identified, assessed, and weighted in a conjoint study.

### 4.1 Perception and Acceptance of CCU Deployment Scenarios

In line with other empirical studies assessing CCU acceptance (Arning et al., 2017; Jones et al., 2016; Perdan et al., 2017), the CCU technology was positively perceived by most respondents. Compared to general acceptance, the local acceptance, i.e., the acceptance of a CCU site in the surrounding neighbourhood, was lower, but still backed by the majority.

Apart from general evaluations of CCU technology acceptance, the present study yielded insights into the acceptance of design parameters of CCU site deployment scenarios. The most important criterion was the *profitability* of an industrial CCU project. This is in line with findings, where economic considerations were identified as most important predictor of renewable energy acceptance in Germany (Zoellner et al., 2008). Even with a strong involvement of public funding, the approval for a CCS site was 55%. If it was possible to operate a CCU site profitably, the acceptance increased to 77%. Another indicator for the strong influence of profitability can be seen in the findings of the sensitivity analysis (scenario 3): the most preferred product (fuel) is not attractive enough to achieve high acceptance levels – a prerequisite for reaching public acceptance is a cost-effective production. For CCU deployment scenarios we can conclude, that an economic process route is always preferred by the public. Future technical CCU research should, therefore, be directed on the development of profitable deployment scenarios and business models. However, depending on the scenario, start-up financing is also accepted, whereas long-term financing of the CCU technology is generally rejected.

The type of *$CO_2$-derived product* also exerted considerable impact on preferences. Apparently, the public integrates the technology process outcomes, i.e., the different types of $CO_2$-derived products, into the assessment of the technology and its infrastructure. Looking at the different CCU product types, the fuel option was the most preferred. When using $CO_2$ for fuel production, many participants perceived the protection of fossil resources as a key advantage, given the high fuel demand worldwide and the high value of maintaining individual motorized mobility. On the other hand, the near-time combustion of the CCU fuel and thus, the rapid release of the previously bound $CO_2$ was perceived critically. Since the fuel production based on the CCU technology is a highly energy-intensive process, future CCU fuel production scenarios should also integrate the energy supply and implications for power system and infrastructure design. Moreover, future technical research should improve the economic efficiency of this process route to achieve a higher acceptance of the CCU technology.

Using the CCU technology to produce drugs represents another positively perceived use case in the context of CCU. However, in focus group discussions respondents criticized the comparably small amount of $CO_2$ being used (and saved) in drug production and unknown health consequences of using $CO_2$ for edible products. These perceptions can be explained by inaccurate mental models of laypeople, where $CO_2$ is perceived as a toxic substance, causing negative health effects (e.g., headaches, suffocation) (van Heek et al., 2017a).

The production of fertilizer based on $CO_2$ was neutrally perceived. Similar to the perceptions of $CO_2$-derived drug coating, negative perceptions of the $CO_2$-derived fertilizer were related to health concerns due to the "toxic" nature of $CO_2$. We assume that the perceived closeness of the product to the body is the underlying explanatory variable: the closer the (potentially harmful) innovative product is to the own body, the more threatening it is perceived, leading to more negative product evaluations.

Compared to the other product alternatives, the mattress received the most negative preference ratings. Even though the savings of fossil resources in the production of the mattress were acknowledged as environmental benefit, the unknown health consequences of long exposure times to a $CO_2$-derived mattress acted as strong barrier. Interestingly, the CCU mattress received more positive acceptance ratings, when it was the only CCU product example being evaluated (e.g., Arning et al., 2017; van Heek et al., 2017b). We assume that the direct comparison of CCU product alternatives and their preference assessment in holistic scenarios caused these different outcomes. Hence, for a valid estimation of CCU technology and product acceptance a multi-method approach and mutual validation or triangulation of findings is strongly recommended.

The *source of $CO_2$* was the least acceptance-relevant design parameter in the CCU deployment scenario. However, for a successful technical rollout of CCU, $CO_2$ should be taken from chemical and/or steel industry to avoid any decline in acceptance. Since $CO_2$ cannot yet be separated from steel industry emissions, the $CO_2$ capacities of the chemical industry should be fully exploited. If, nevertheless, $CO_2$ is extracted from coal-fired power stations, a profitable operation and an acceptable product is necessary to reach public acceptance of CCU deployment.

### 4.2 Methodological Considerations and Future Research

The present study successfully demonstrated the assessment of public acceptance and preferences for specific technology scenario criteria. Even though the awareness and knowledge about (future) deployment scenarios of the CCU technology was rather low, respondents were able to express clear preferences regarding the source of $CO_2$, the manufactured CCU product variants, and the profitability of running the CCU site. The empirically based acceptance evaluations can be used as additional evaluation parameter in life-cycle assessments, where not only the environmental impact of specific technology routes is evaluated, but also their impact on public acceptance. Since this study was a first attempt to assess acceptance of specific CCU site deployment scenarios, we did not fully portray the complete technical life-cycle of CCU in our study. On the other hand, qualitative studies about CCU product acceptance suggest, that potential consumers integrate dimensions into their acceptance evaluations, which are not considered in life-cycle analyses so far, such as the disposal of CCU products (van Heek et al., 2017b). From a technical point of view, the disposal of a product is not considered in life-cycle analyses, since this process step does not differ for conventionally manufactured or CCU-based products. However, for the consumer the disposal step (especially the way of disposal) is highly acceptance-relevant and strongly influences the overall perception of the CCU technology. Future studies should, therefore, extend the acceptance evaluation of the CCU life-cycle to gain a more complete picture of acceptance and acceptance-relevant "hot spots" in CCU scenarios. Moreover, we work on the extension of this methodological approach to other innovative and sustainable technical scenarios (e.g., alternative fuels). Since sustainable technical innovations do not only exert environmental, but also economic impacts, market-mediated effects should also be systematically considered in future life-cycle approaches, such as suggested in the Consequential LCA (CLCA) (Kätelhön et al., 2016).

However, the low awareness level of CCU bears the risk of assessing instable and nonvalid pseudo-opinions about CCU. To reduce this risk, we put special emphasis on the development of the instruction in cooperation with technical experts and iteratively improved their comprehensibility in pre-tests.

## 5 CONCLUSIONS

Combining social science methodologies with technical and economic assessment approaches allows to include the complex concept of public acceptance in sustainable technical scenario development and respective life-cycle steps. Moreover, the blending of acceptance into life-cycle assessments allows the definition of an optimal consumer product life-cycle scenario. This way, sustainable technical innovations have a higher chance of being acceptable and commercially successful, when a conjunct development of technology, sustainability, and acceptance is pursued.

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