



Two Sides of the Same Coin—Explaining the Acceptance of CO₂-Based Fuels for Aviation Using PLS-SEM by Considering the Production and Product Evaluation

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In the present study, we studied the acceptance of CO₂-based fuels for aviation as a product manufactured using Carbon Capture and Utilization (CCU). CCU can be regarded as the cornerstone for a circular approach. We focused on understanding whether the evaluation of CCU as a production method is related to the social acceptance of the resulting product. We applied an empirical quantitative approach using an online questionnaire targeted at German, Spanish, Dutch, and Norwegian respondents ($N = 2,187$). For both CCU and the fuel, lay perceptions in terms of perceived benefits and barriers were assessed, as well as their affective evaluation. Additionally, the acceptance of the end-product was surveyed. Using partial least squares structural equation modeling (PLS-SEM), we gained a better understanding of how the acceptance of CO₂-based fuels for aviation is formed. We found that the evaluation of CCU was mainly indirectly related to the acceptance of the product through relationships with the evaluation of the fuels. The perception of the benefits of CCU did affect the benefit perception of CO₂-based fuels the most, followed closely by the affective evaluation of the fuels. For the perception of the barriers of CO₂-based fuels, the perceived barriers of CCU were again the strongest predictor, followed by the affective evaluation of the fuels. We identified a moderate predictive power for the acceptance of CO₂-based fuels. The relationship with the perceived benefits of the fuels was the most relevant, followed by barrier perceptions, the affective evaluation of the fuels, and finally the benefit perception of CCU. Overall, the findings yield first insights into the role of the evaluation of CCU and CO₂-based fuels for aviation for the formation of the product's acceptance. The outcomes are useful for informing the product's and CCU's technical development and policy making. Additionally, they aid in the design of public information about CCU and support the development of sensible communication strategies for the successful market roll-out of CCU and CO₂-based fuels.

Keywords: CO₂-based fuels for aviation, carbon capture and utilization, social acceptance, perception, affective evaluation, PLS-SEM

1 INTRODUCTION

In parallel with the growing public awareness of climate change and its potential consequences for future life on Earth, the number of (international) research efforts aiming to mitigate climate change has significantly increased in recent years (Foley et al., 2017). When supported by technical, economic, and political systems, such efforts might help to reduce the use of fossil resources by increasing the roll-out of renewable energy sources. Additionally, they could help to integrate more efficient processes and production lines that will reduce energy consumption altogether. In this regard, another aim is to develop green products, such as low-carbon chemicals and materials, that are produced with a circular economy in mind (Tenhunen and Pöhler, 2020). A circular economy refers to the use of multiple methods from different fields—e.g., science, process engineering, economics, ecology, and policy—to target closed material cycles, develop or rearrange production chains, and reframe consumption behaviors (Moreau et al., 2017; Morsetto, 2020). Alongside standardized approaches such as techno-economic and life cycle analyses, within a frame of reference, material and energy flows are analyzed and compared. In this way, ecological and environmental effects, resource depletion, and potential human-health consequences can holistically be assessed (Klöppfer, 2014; von der Assen and Bardow, 2014; Finkbeiner, 2014; International Standard Organization, 1997).

It is increasingly understood that circular economy efforts have strong social, policy, and governance components (Sovacool et al., 2015; Moreau et al., 2017; Boudet, 2019; Kirchherr and Piscicelli, 2019; Hartley et al., 2020), even though the majority of research activities still focus on technical and economic factors. Sovacool and colleagues (Sovacool et al., 2015; Sovacool et al., 2018) called for the systematic and consequent integration of social science knowledge and methods in the development and deployment of energy systems. In this way we can learn about the perception of potential barriers and risks of novel energy technologies (Slovic and Peters, 2006; Huijts et al., 2012; Emmerich et al., 2020), and use the social acceptance of these innovations for a successful energy transition (Moreau et al., 2017; Boudet, 2019). This is possible because studies on public perception and social acceptance can inform technical research and industry efforts about potential acceptance pitfalls quite early on in the development process (Arning et al., 2020). Additionally, such studies can help to launch public information strategies (Offermann-van Heek et al., 2020; Kluge et al., 2021), as well as tailor public education (Liebe and Dobers, 2019; Hartley et al., 2020) to the needs of consumers. Last, but not the least, acceptance research helps to foster a transparent communication between all involved stakeholders (Zaubrecher and Ziefle, 2016; Boudet, 2019; Kluge et al., 2021) and might help to integrate and educate the public about the economic and ecological necessity to systematically rethink technology development in line with sustainability.

In the last couple of years, a general increase in studies dealing with social acceptance in renewable energy technologies can be observed. Such studies both deal with the acceptance of different energy technologies—e.g., wind (e.g., Devine-Wright et al., 2017; Fischhendler et al., 2021), biomass (e.g., Mather-Gratton et al.,

2021), solar (e.g., Kratschmann and Dütschke, 2021), and hydrogen (e.g., Ricci et al., 2008)—and different CO₂-based end products—like fuels (Linzenich et al., 2019b; Engelmann et al., 2020) and insulation boards (Arning et al., 2021; Simons et al., 2021). Nevertheless, few studies combine public perception and acceptance while investigating more than one aspect or production step relevant from a circular economy perspective (Arning et al., 2018b; Offermann-van Heek et al., 2020).

In line with this research gap, this work studied the acceptance of one example of a product produced using the circular economy technology Carbon Capture and Utilization (CCU): CO₂-based fuels for aviation¹. CO₂-based fuels are not an entirely circular product yet. However, it can be integrated within a circular economy approach in the sense that—in contrast to the rather linear production and consumption of traditional jet fuel from fossil resources—the CO₂-based fuel production pathway “bends” the line (to become a curve) and CO₂ use from direct air capture would then be the final step to complete circularity (to make the curve become a circle). This change would be different to the traditional production and consumption of jet fuel from fossil resources in the sense that the traditional process chain is linear in the prevailing linear economic model. We focused on understanding whether the social acceptance of the product is related to the public perception of CCU as the technology used to produce it. More specifically, we aimed to get a better understanding of whether, and if so to what extent, end users include their perception of CCU in their acceptance judgment of the product, rather than merely considering their evaluation of the product itself. To our knowledge, no previous study considered this aspect for any CO₂-based product.

The present article first establishes a theoretical basis for the study’s aim. We then outline the logic of the empirical procedure alongside the research question and hypotheses. Next, we describe the measurement instrument and method, including a description of the sample and an explanation of the applied partial least squares structural equation modeling approach. Subsequently, the results section provides insights into the evaluation of CCU and CO₂-based fuels and presents the identified structural model and its quality evaluation. Finally, the findings are discussed and the limitations and prospects for future research are outlined.

2 PRODUCTION OF CO₂-BASED FUELS AS A LOW-CARBON AND SUSTAINABLE ALTERNATIVE

CCU is a circular economy approach that is currently being developed and employed. The main idea behind CCU is to reuse captured CO₂ as feedstock for the production of carbon-based materials and products (von der Assen and Bardow, 2014). In this way, CCU not only is valuable because of its potential

¹In the remainder of this work (CO₂-based) fuels always refer to CO₂-based fuels for aviation.

contribution to mitigating climate change (Kätelhön et al., 2019), but also enables the more sustainable production of a variety of products: chemicals such as ethylene, methanol, and olefines (Kätelhön et al., 2019; Mustafa et al., 2020); also products such as construction materials, polymers, and fuels can be produced by using the CO₂ for mineral carbonation (Zimmermann et al., 2020b; Chauvy and De Weireld, 2020). Through the production of CO₂-based fuels, CCU can help to supply energy sources to nonelectrifiable mobility sectors that experience difficulties in switching to carbon-free fuel alternatives such as hydrogen. An example of such a mobility sector is the aviation sector (International Energy Agency, 2019).

Nevertheless, there are still some hurdles to overcome before the implementation of CCU reaches its full potential. First, the conversion of CO₂, as well as several other production steps, can be energy-intensive (Zimmermann et al., 2020a). To ensure an overall carbon-neutral CO₂ reuse, enough low-carbon energy sources must thus be available (Wich et al., 2020). Moreover, the widespread industrial implementation of CCU requires the construction of new plants, or adaptation of existing ones. This can include high-pressure processes and involves high investment costs. Additionally, all of this will happen in a sector that knows a slow market adoption (Zimmermann et al., 2020a). However, when these conditions for CCU are met, estimations predict that the greenhouse gases (GHG) emitted during the production of one ton of CO₂-based fuel—measured in CO₂ equivalents (CO₂e)—could be 34% less than the GHGs emitted during the production of one ton of a reference conventional fuel (Zakkour et al., 2018).

There are multiple ways to produce CO₂-based fuels: e.g., Fischer-Tropsch-synthesis that converts syngas into liquid hydrocarbons, or the production of methanol, dimethyl ether, or oxymethylene ether (e.g., Matzen and Demirel, 2016; Bongartz et al., 2018; Deutz et al., 2018; Dieterich et al., 2020). In the present study we considered a CCU process based on the separation of CO₂ from the flue gas streams of the exhaust of industrial plants, before the CO₂ is emitted. There are also several possible processes to separate the CO₂ from the flue gas, i.e., membrane adsorption, cryogenic separation, or the use of a physical solvent (Mustafa et al., 2020). Depending on the source of the flue gas, it can be necessary to purify the captured CO₂ before reusing it. If this is the case, the applied purification procedure depends on circumstances such as the CO₂ output flow rates and the type of impurities in the stream (Pieri et al., 2018; Pires da Mata Costa et al., 2021). After purification, the previously compressed CO₂ in some cases requires (if it is not converted in the existing plant) transport through pipelines, or using trucks or trains, depending on the properties of the gas stream and other external factors, such as transport distance (Pieri et al., 2018). Finally, the CO₂ is converted into CO₂-based fuels. The present study assumed a direct electrocatalytic conversion in a co-ionic membrane reactor. During the conversion, CO₂ is converted into chemical energy carriers in the form of hydrocarbons. The eCOCO₂ project and its interdisciplinary consortium² is studying this approach (eCCO₂, 2016).

²<https://ecocoo.eu/>.

3 SOCIAL ACCEPTANCE OF SUSTAINABLE TECHNOLOGIES

For CCU, as for all other sustainable innovations and related products and technologies, its social acceptance is a prerequisite for its successful market adoption. In the past, it has become apparent that in the case of renewable energy sources such as wind turbines a lack of local acceptance can manifest itself in the form of active protest (Ellis and Ferraro, 2016; Scherhauser et al., 2017; Azarova et al., 2019). For these reasons, knowledge on the acceptance, and drivers of the acceptance, must be integrated in the development and deployment of innovations. To gather this knowledge, communication and social science methodologies should be incorporated in research efforts. Misperceptions about public attitudes, which could lead to erroneous decisions and miscommunication, can then be prevented by means of a thorough investigation of factors influencing acceptance, thereby also decreasing the chance of protests or opposition (Devine-Wright et al., 2017). Furthermore, the social insights can be used to regard the public's information needs when formulating targeted communication strategies. This allows the public to make decisions based on objectively oriented information (Offermann-van Heek et al., 2020). Altogether, the importance of the integration of social technology acceptance has increased in recent years, as can be derived from its inclusion in studies in fields like policy making and analysis (Akerboom et al., 2020; Bjørnå vold et al., 2020), and supply chain design (d'Amore et al., 2020).

According to the classification of Wüstenhagen et al. (2007), the social acceptance of sustainable, or renewable, technological innovations consists of three dimensions. First, the socio-political acceptance refers to the general acceptance or public support of a technology. For CCU, this refers to both the general technological approach of recycling CO₂ by converting it into other products, as well as the usage of these end products. Second, community acceptance describes the local acceptance of those who personally experience proximity to a CCU plant, e.g., because of the location of their home or their role as local decision makers. These stakeholders can show a positive attitude through acceptance, or a negative one through a rejection of the technology which possibly results in protests. Finally, the third dimension regards the market acceptance, which specifically refers to the acceptance and adoption by the consumers and investors. To understand the social acceptance of a sustainable technology, these three dimensions need to be studied separately, in combination with each other, and over longer periods of time.

We defined *acceptance* as the active adoption of a sustainable technology or product, to be distinguished from a merely reactive acceptance of the technology or product (Dethloff, 2004). In its most basic form, acceptance can thus be seen as a general willingness to use the innovation. In a broader perspective, acceptance also covers the underlying cognitive perceptions of a technology (e.g., assumptions and mental models about a technology, (perceived) knowledge as well as factual domain knowledge) and its affective evaluation (feelings, risk affects, and concerns about the innovation and the technology) (Huijts et al., 2012; Arning et al., 2019; Huijts et al., 2019;

Linzenich et al., 2019b). There is empirical evidence that acceptance can be regarded as adoption decision of persons to (not) use a technical product and this decision is influenced by cognitive and affective (risk) evaluations (Joffe, 2003; Linzenich et al., 2019b; Huijts et al., 2019; Engelmann et al., 2020). Going a step further, it also includes actions and attitudes that manifest itself in the active support of the innovation, for example by speaking out and promoting it (Huijts et al., 2012). Finally, the acceptance of a sustainable innovation could be manifested in a preference for the technology or product compared to comparable conventional alternatives. For that reason, previous research has often weighed the preference of individual product or production attributes, such as fuels, against one another to determine which technology and technological circumstances are most preferable (e.g., Hackbarth and Madlener, 2013; Hackbarth and Madlener, 2016; Linzenich et al., 2019a). We therefore also included the preference for a sustainable technology or product, compared to previously used conventional approaches, in our interpretation of acceptance. Altogether, acceptance is a complex construct which is challenging to accurately capture directly, especially if it regards generally unknown innovations (Fine, 1986; Sinkovics et al., 2002). It is assessed by measuring a behavioral intention, since the intent of a planned future action has a direct influence on acceptance, as has been noted in previous models that studied social acceptance in the context of sustainable energy technologies (e.g., Huijts et al., 2012; Broman Toft et al., 2014; Arning et al., 2021).

4 SOCIAL ACCEPTANCE OF CARBON CAPTURE AND UTILIZATION (PRODUCTS) AND CO₂-DERIVED FUELS

One part of the social science studies on CCU-related topics is dedicated to examining the *CCU technology* in general and the underlying infrastructure and process steps. Besides the practical challenges associated with CCU that must be tackled to implement the technology on a widespread basis—i.e., technical issues, high costs, and legal barriers (Scheelhaase et al., 2019), these studies helped to identify the barriers laypeople perceive as part of the public perception of CCU. Although laypeople's perceptions are not necessarily factual risks, gaining an understanding of these perceived risks and (usage) barriers is necessary to be able to design communication strategies and clarify misconceptions that could lead to a rejection of the technology and its products (Engelmann et al., 2020). One such often identified barrier regards CCU's questionable sustainability. Laypeople, e.g., think that CCU is an excuse to continue emitting CO₂ or that increased CO₂ emissions are merely delayed (Jones et al., 2014; Arning et al., 2017). Interestingly, whereas laypeople were ambivalent about the existence of unidentified risks of CCU as a technology, potential health risks resulting from the technology's deployment were rather dismissed (Offermann-van Heek et al., 2018).

Besides the barriers, studies also identified the perceived benefits of the CCU approach. Generally speaking, the public perceives CCU as beneficial and useful (Arning et al., 2018a). The best evaluated benefits are environmental, e.g., it buys more time in the mitigation of climate change, reduces the use of fossil resources, and reduces CO₂-emissions (Jones et al., 2014; Jones et al., 2017). Another example of a perceived advantage was the possible economic benefit of CCU, e.g., because of job generation (Offermann-van Heek et al., 2018).

Regarding the general acceptance of CCU, it was found to be positive, but tentative with scores not much higher than the midpoint of the scale, whereas local acceptance of CCU installations was still moderate but somewhat lower (Arning et al., 2020). In another study, CCU was found to be more positively accepted than Carbon Capture and Storage (CCS), in which the captured CO₂ is merely stored instead of reused (Arning et al., 2019). Moreover, some previous studies focused on understanding the drivers behind the acceptance of CCU. Arning et al. (2018b) found that as a CO₂ source, a steel plant was preferred over a chemical or coal-fired plant. The study also found that for the acceptance of CCU, profitability is the most decisive factor, thereby being more important than the obtained end product and the source of the CO₂. Nonpublic financing was the preferred way to make CCU profitable, indicating that there is little willingness to pay for the implementation of CCU installations among laypeople. In line with the theories described in **Section 3**, other studies found that the acceptance of CCU primarily increases as the benefits for the technology are increasingly perceived. An increase in acceptance was also seen when the technology was increasingly perceived to be mature and innovative. Contrarily, perceived barriers—e.g., risks connected to the use and disposal of CCU products—have been found to reduce the acceptance (Linzenich et al., 2019b; Offermann-van Heek et al., 2020).

As aforementioned, the specific acceptance of CCU products should be included in acceptance studies as well. Even though laypeople perceived relatively few barriers for such products, sustainability doubts, increased (energy) costs, and a possibly reduced product quality were still identified as possible acceptance hurdles (Jones et al., 2014, 2015; Arning et al., 2017; Arning et al., 2018a). Regarding the benefits of CCU consumer products—e.g., mattresses—laypeople again perceived environmental and economic benefits, e.g., the contribution to climate change mitigation and job opportunities, respectively (Jones et al., 2015; Arning et al., 2018a).

CCU products are generally positively accepted. The products studied so far include CO₂-based mattresses and beverages infused with recycled CO₂ (Offermann-van Heek et al., 2018). Their acceptance is usually reflected in laypeople's expressed willingness to use and buy CCU products (Arning et al., 2018a). Moreover, van Heek et al. (2017b) identified acceptance-relevant factors for CCU products. These included the disposal conditions and the saved fossil resources resulting from their replacement by CO₂. Contrarily, the amount of CO₂ that can be stored in a product was less relevant for its acceptance. Additionally, the benefit and barrier perceptions of the CCU

products had a direct positive and negative effect, respectively, on the acceptance of the products (Offermann-van Heek et al., 2018).

Regarding specific CCU products, some studies found CO₂-based fuels to be the preferred CCU product compared to other possible manufactured goods, such as e.g., fertilizer or mattresses (Arning et al., 2018b; Offermann-van Heek et al., 2018). In general, laypeople assessed CO₂-based fuels to be safer, more eco-friendly, less toxic, cleaner, and less harmful than their conventional counterparts (Engelmann et al., 2020). The product was also better accepted than the individual CCU production steps—the capture, transport, and conversion of CO₂—required to make the product (Offermann-van Heek et al., 2020).

Finally, a few studies have started to build a bridge between the evaluation of CCU as a technology and the resulting products. Lutzke and Árvai (2021) found that for carbonized beverages, the source from which the CO₂ is captured can influence the willingness to use a resulting CO₂-based product. In this case, an increased negative evaluation of CCU also decreased the product's acceptance. Arning et al. (2018a) did study laypeople's perceptions of CCU and mattresses as a CCU product in a single study, but did not examine possible relationships between the two evaluations. Additionally, Offermann-van Heek et al., 2020 identified a rather small fuel production site in the form of a biogas plant, which does not require the transport of CO₂, as the best case scenario for the production of CO₂-based fuels. However, their methodology does not allow the derivation of conclusions about the role of the perception of the infrastructure on the perception of the product. The first approaches to dovetailing CCU as a technological process with the resulting products have thus been established, but both aspects still need to be combined in a detailed and systematic way.

5 DERIVATION AND JUSTIFICATION OF EMPIRICAL PROCEDURE

Since the acceptance of CCU is a complex phenomenon for which multiple dimensions and stakeholders should be considered (Wüstenhagen et al., 2007), acceptance studies should focus not only on understanding the acceptance of CCU as a technology, but also on the acceptance of the resulting CCU products. We believe that the latter is thereby of especially great importance because without the public's adoption of the products—through the subtle act of choosing, or at least tolerating, them—the CCU technology will not be able to thrive. Additionally, a rejection of the produced CCU products will lead to a loss of resources such as time and investments used to employ the CCU technology. For these reasons, this study focused on obtaining a better understanding of the public acceptance of CO₂-based fuels for aviation as an example of a CCU product. As such, it considered aspects of the socio-political and market acceptance proposed by Wüstenhagen et al. (2007) (Section 3).

However, we recognize that the acceptance and perception of CCU as a production method is important as well. A strong

rejection of the technology could hinder its successful roll-out if it leads to active opposition and protests or lack of funding. Additionally, one could assume that the consumers use their evaluation of the technology when evaluating the resulting product, since CCU products cannot exist without the CCU production technology. Even though the findings discussed in Section 4 show that studies have gathered diverse insights on several aspects of both CCU as a technology and the resulting products, to our knowledge, the relationship between the evaluation of CCU and the acceptance and evaluation of CCU products has not been covered in previous studies. Based on this research gap, we formulated the following research question to guide the study described in the present article:

What role, if any, does the evaluation of CCU as a production method play in the formation of the acceptance of CO₂-based fuels for aviation as an example of a CCU product?

Answering this research question could be very valuable for the design of communication strategies for the product's and technology's market roll-out, since it helps to pinpoint what the communication should focus on.

5.1 Hypotheses

Because of the explorative approach of the study, we defined a broad range of hypotheses to aid in answering the research question. We thereby focused on the cognitive and affective evaluation of the technology and product as possible drivers behind acceptance (Huijts, 2018). These evaluations are assumed to have a greater influence on the formation of acceptance than, e.g., the demographic characteristics of the respondents (Liu et al., 2019).

First, the cognitive determinants include the perceived benefits and barriers (Liu et al., 2019). As aforementioned, the role of such perceptions of a product or technology on the acceptance of that product or technology has been well established by previous theories and findings (e.g., Huijts et al., 2012; Arning et al., 2020; Engelmann et al., 2020). In line with these previous findings, as well as our goal of exploring the possible relationships between CCU and the acceptance of CO₂-based fuels for aviation, we propose the following hypotheses:

- H1_a:** The benefit perception of CO₂-based fuels is positively related to the acceptance of CO₂-based fuels.
- H1_b:** The barrier perception of CO₂-based fuels is negatively related to the acceptance of CO₂-based fuels.
- H1_c:** The benefit perception of CCU is positively related to the acceptance of CO₂-based fuels.
- H1_d:** The barrier perception of CCU is negatively related to the acceptance of CO₂-based fuels.

In this regard we also explored the possibility of indirect relationships through relationships between the perception of CCU and the perception of CO₂-based fuels using the following hypotheses:

- H2_a:** The benefit perception of CCU is positively related to the benefit perception of CO₂-based fuels.

H2_b: The benefit perception of CCU is negatively related to the barrier perception of CO₂-based fuels.

H2_c: The barrier perception of CCU is positively related to the barrier perception of CO₂-based fuels.

H2_d: The barrier perception of CCU is negatively related to the benefit perception of CO₂-based fuels.

Second, the cognitive determinants are distinguished from the affective attitude toward a technology or product. Affect can be regarded as an emotional evaluation that is made rather intuitively (Slovic and Peters, 2006; Cousse et al., 2020). This has been found to affect judgments directly, as well as through its relationship with perceived risks—in our case barriers—and benefits (Finucane et al., 2000; Linzenich et al., 2019b). For this we proposed the following hypotheses:

H3_a: The affective evaluation of CO₂-based fuels is positively related to the acceptance of CO₂-based fuels.

H3_b: The affective evaluation of CO₂-based fuels is positively related to the benefit perception of CO₂-based fuels.

H3_c: The affective evaluation of CO₂-based fuels is negatively related to the barrier perception of CO₂-based fuels.

H3_d: The affective evaluation of CCU is positively related to the acceptance of CO₂-based fuels.

H3_e: The affective evaluation of CCU is positively related to the benefit perception of CCU.

H3_f: The affective evaluation of CCU is negatively related to the barrier perception of CCU.

Finally, the possible relationship between the affective evaluation of the technology and the evaluation of the product was explored as well:

H4_a: The affective evaluation of CCU is positively related to the affective evaluation of CO₂-based fuels.

H4_b: The affective evaluation of CCU is positively related to the benefit perception of CO₂-based fuels.

H4_c: The affective evaluation of CCU is negatively related to the barrier perception of CO₂-based fuels.

6 METHODS

In this section, we will cover the used measurement instrument, data collection and preparation approach, final sample, the applied PLS-SEM procedure, and the additional statistical tests.

6.1 The Measurement Instrument

As a measurement instrument, we used a quantitative online questionnaire generated using the survey software by *Qualtrics*³. Porter et al. (2019) and Lotz (2020) For the development and selection of items for the questionnaire different sources were consulted: 1) input from previous (CCU) acceptance studies (Section 4); 2) discussions and exchange with project partners of

the *Horizon2020 eCOCO₂* consortium² (supported by literature review (e.g., Porter et al., 2019 and Lotz, 2020)), in combination with; 3) validated items scales if available. All items included in the analysis can be found in the supplementary materials (**Supplementary Table S1**). The original German questionnaire was translated for its use in Spain, Norway, and Netherlands. Whereas the German and the Dutch versions were prepared within the authors' group, a translation agency was consulted for the Norwegian and Spanish translations. All translated surveys were subsequently pretested and cross-checked by native speakers of the respective languages. Moreover, the ethical board of the Faculty of Humanities at RWTH Aachen University checked and approved the survey's ethical acceptability.

Before starting, the respondents completed a few screening questions to control for a representative sample—regarding nationality, age, gender, education, and home region—of respondents between 18 and 70 years of age. Subsequently, the respondents received a brief introduction on the survey's topic, were reminded of their rights, and informed on how the data would be handled [with regard to the data privacy standards of the DSGVO (Schwartz, 2019)].

In the main part of the questionnaire, question blocks were alternated with increasingly detailed explanations of the production process. The provided explanations were easily and objectively formulated, and checked for technical correctness by experts in the field of CCU⁴. The first explanation briefly covered the overall production process of CO₂-based fuels using CCU. This allowed the respondents to indicate their affective evaluation, benefit perception, and barrier perception of CCU as a production process for the fuels. In the subsequent parts of the questionnaire, the respondents received five further, more detailed, explanations covering: the separation, purification, transport, and conversion of CO₂, as well as CO₂-based fuels for aviation as an end product. This enabled the respondents to then indicate their affective evaluation, benefit perception, barrier perception, and acceptance of CO₂-based fuels for aviation.

In **Section 6.4.2** the used questions are considered in more detail. All multiple-item measurements used six-point scales—ranging from 0 = *most negative answer* to 5 = *most positive answer*. Within the questionnaire blocks queried with Likert scales, the statements to be evaluated were presented in a randomized order.

6.2 Data Collection and Preparation

Data were collected in the fall of 2020 using the paid services of a market research company. Data collection targeted German, Dutch, Spanish, and Norwegian respondents. To ensure a good quality dataset the survey included two quality checks, during which the respondents were asked to select a specific response and were marked as *failed quality check* if they failed to do so. After this quality check and further cleaning⁵ we ended up with a final dataset

⁴An English translation of these explanations can be found in the supplementary material.

⁵From the sample of 9,738 participants who at least started the survey, respondents were removed because of: full quotas; incomplete data sets; speeding, i.e., all participants whose response time was below 35 percent of the median duration, and; internally inconsistent answering patterns, i.e., cases that indicated (dis)agreement for two items phrasing the same statement oppositely.

³<https://www.qualtrics.com>.

of $N = 2,187$ respondents. On average, participants took 23.2 min ($SD = 9.6$ min) to fully complete the survey.

If necessary, we recoded the data so that 0 always referred to the most negative answer from the question's point of view, and 5 to the most positive. We also computed a grouping variable for the respondents' education. The different nationalities received a different question on their highest achieved level of education in line with the used system in the respective countries. We grouped the answers to these questions into a single variable using a low, medium, and high level of education based on the International Standard Classification of Education (ISCED)⁶ (Eurostat Statistics Explained, 2011). An overview of the grouping can be found in the supplementary material (**Supplementary Tables S2–S5**).

6.3 Sample

Of the $N = 2,187$ respondents in the sample after cleaning, 48% were male ($n = 1,052$) and 52% were female ($n = 1,135$). By design, the ages ranged between 18 and 70 years (fixed quotas set for each country). The average age was $M = 45.0$ ($SD = 14.5$). Most of the respondents completed a medium ($n = 1,005$, 46%) or high ($n = 820$, 37%) level of education. A relatively small share of the respondents completed a low level of education ($n = 362$, 17%). Finally, of the respondents, 25% were German ($n = 543$), 25% were Spanish ($n = 545$), 25% were Dutch ($n = 549$), and 25% were Norwegian ($n = 550$). In the supplementary material, **Supplementary Table S6** depicts how well the collected sample represents the aimed sample, which was based on the representative distributions in the included countries. Regarding age and gender, our sample represented the respective populations fairly well. However, for the respondents' education and region there were more discrepancies. Additionally, **Supplementary Table S7** in the supplementary material summarizes the descriptive data for the constructs in the final model (**Section 7.2**) for each country. Even though occasional differences between the included countries occurred, the present study aimed to take a cross-national, pan-European view. We therefore only use and interpret the overall sample in the remainder of the present article.

Finally, we also assessed the participants' previous experience with CO₂-based fuel production using three items⁷. Overall, we found that the previous experience with CO₂-based fuel production was rather low ($M = 1.6$, $SD = 0.3$) for all countries (Norway: $M = 1.2$, $SD = 0.9$; Germany: $M = 1.5$, $SD = 0.8$); the Netherlands: $M = 1.6$, $SD = 0.9$; Spain: $M = 2.0$, $SD = 0.9$).

6.4 Partial Least Squares Structural Equation Modeling (PLS-SEM)—Procedure

In this subsection, we report on the PLS-SEM procedure starting with the theoretical background of the methodological approach,

followed by the description of how the model selection was accomplished. We also outline the procedures of model specification and evaluation. The latter includes the reflective and formative measurement evaluation, as well as the structural model evaluation.

6.4.1 Partial Least Squares Structural Equation Modeling

To test the hypotheses introduced in **Section 5**, we applied partial least squares structural equation modeling (PLS-SEM). As extensively described by Hair et al. (2017), SEM is a multivariate analysis technique. It thus allows the simultaneous exploration of multiple variables. Although other kinds of SEM exist as well, the PLS approach is especially well equipped for exploratory research. A model designed using PLS-SEM consists of two model layers that are analyzed simultaneously. The first is the *measurement model* (*outer model*). In social science research, the concepts included in a study are often abstract and cannot be measured directly. Instead, they are measured using several items (manifest variables, indicators) which are then combined to form a construct (latent variable) (Sarstedt et al., 2016). The relationships between the included constructs and their indicators are referred to as the *measurement model*. The second is the *structural model* (*inner model*), which consists of the relationships between the different constructs. In the present study, the *structural model* will be used to evaluate the hypotheses.

There are two ways to measure latent variables which are represented differently in the *measurement model*. For *reflective measurements*, the indicators “are considered to be error-prone manifestations of an underlying construct with relationships going from the construct to its indicators” (Bollen, 1989; as cited in Sarstedt et al., 2016, p. 4000). Such indicators can thus be seen as “a representative sample of all the possible items available within the conceptual domain of the construct” (Nunnally and Bernstein, n.d., as cited in Sarstedt et al., 2016, p. 4000). To give an example, in our study, the construct of *support* (**Section 6.4.2**) can be considered as an example for reflective measurement, as statements about one's support of an object are interchangeable and omitting a supporting statement does not change the content of the construct. For *formative measurements* “the indicators form the construct by means of linear combinations” (Diamantopoulos, 2006, as cited in Sarstedt et al., 2016, p. 4000). Contrary to reflective measurements, the values of the indicators of formative measurements are not assumed to have the construct as a common cause. Instead, the indicators are aspects of the construct and the relationships run from the indicators to the construct (Hair et al., 2017, p. 73). Formative constructs are present, for example, in the case of *barriers* and *benefits* of a technology, since omitting a beneficial or detrimental facet can change the content of the construct.

Additionally, our *measurement model* included single-indicator constructs—which are reflective by nature—as well as higher-order constructs (HOCs). In a HOC, several lower-order constructs (LOCs) act as the indicators of the construct.

⁶[https://ec.europa.eu/eurostat/statistics-explained/index.php/International_Standard_Classification_of_Education_\(ISCED\)#Implementation_of_ISCED_2011_28levels_of_education.29](https://ec.europa.eu/eurostat/statistics-explained/index.php/International_Standard_Classification_of_Education_(ISCED)#Implementation_of_ISCED_2011_28levels_of_education.29).

⁷1: “I have a great interest in the production of CO₂-based fuels.”; 2: “I know a lot about the production of CO₂-based fuels.” and 3: “I have never thought about the issue of the production of CO₂-based fuels.”

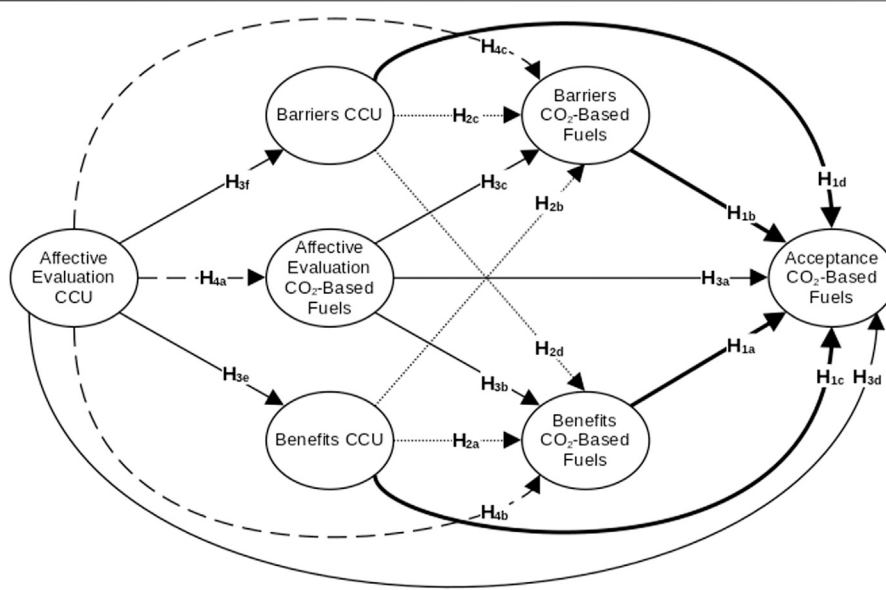


FIGURE 1 | Overview of hypotheses. The thick solid lines indicate the hypothesized direct relationships between perception and acceptance (H₁); the dotted lines indicate the hypothesized relationships between the perception of CCU and the perception of CO₂-based fuels (H₂); the thin solid lines indicate the hypothesized relationships between the affective evaluations and perception and acceptance (H₃); and the long-dashed lines indicate the hypothesized relationships between the affective evaluation of CCU and the evaluation and perception of CO₂-based fuels (H₄).

These LOCs are constructs with their own indicators and measurement type (Sarstedt et al., 2019). In the present study, the use of HOCs allows the easier interpretation of the subcomponents (LOC) that are considered as part of the model’s abstract concepts (HOC).

Finally, in the *structural model*, constructs can be exogenous, endogenous, or both. Exogenous constructs explain (an)other construct(s) in the model, whereas endogenous constructs are being explained by (an)other construct(s) (Hair et al., 2017, p. 46). Since *Affective Evaluation CCU* explains others included in the model, it represents an exogenous construct, whereas *Affective Evaluation CO₂-Based Fuels*—while explaining other constructs itself—is being explained by the former, therefore functioning as an endogenous construct.

6.4.2 Model Specification

We defined our original structural model based on the hypotheses described in Section 5.1. The structural model is depicted in Figure 1. In the graphic, the ovals refer to the structural model’s constructs and the paths run from the exogenous to the endogenous constructs. A complete overview of the constructs, indicators (abbreviations), and items they refer to is provided in Supplementary Table S1 in the supplementary material.

The *Affective Evaluation CCU* (CUAE1—CUAE6) and *Affective Evaluation CO₂-Based Fuels* (FAE1—FAE6) were the only two non-HOC constructs in the model. These constructs referred to the feelings the respondents had about CCU as a production method, and CO₂-based fuels as an end product, respectively. This was measured using two semantic differentials that consisted of the same six opposing adjective pairs. The adjective pairs were inspired by Engelmann et al. (2020). The affective evaluation is likely to be

different if different adjective pairs are used. The constructs thus resemble formative measurements.

The constructs for the benefits and barriers of CCU, and the benefits and barriers of CO₂-based fuels, were HOCs. They were based on benefit and barrier perceptions used in previous studies on CCU (e.g., Arning et al., 2019) and CCU products (e.g., Offermann-van Heek et al., 2018; Engelmann et al., 2020; Simons et al., 2021), as well as extensive discussions with the project partners of the *Horizon2020 eCOCO₂* consortium². These HOCs for the perception also resembled formative measurements because the inclusion of other benefit and barrier aspects likely changes the construct. The multiple-item LOCs for these perception HOCs resembled formative measurements as well, since different items highlighting different aspects of the LOCs likely exist.

The HOC *Benefits CCU* had two multiple-indicator LOCs. The *Environmental Benefits CCU* referred to CCU’s benefits for the environment and consisted of five indicators (CUBEN1—CUBEN5). The *Policy Benefits* referred to policy-related benefits of CCU and consisted of four indicators (CUBEN6—CUBEN9). Additionally, the HOC included two single-indicator constructs that highlighted a specific benefit for which the given name is self-explanatory: *Employment Opportunities* (CUBEN10) and *Raise Awareness CO₂ Reuse* (CUBEN11).

The HOC *Barriers CCU* also had two multiple-indicator LOCs. The *Policy Barriers* referred to policy-related barriers of CCU and consisted of four indicators (CUBAR1—CUBAR4). The *Sustainability Barriers* referred to barriers related to the environmental sustainability of the production method and consisted of four indicators (CUBAR5—CUBAR8). The HOC

also included one single-indicator construct that highlighted a specific barrier: *Scale Barrier (CUBAR9)*, which referred to the observation that CCU will not contribute to the reduction of CO₂ emissions if it is only applied in Europe. The HOC *Benefits CO₂-Based Fuels* only had *Environmental Benefits Fuels* as a multiple-indicator LOC. It consisted of three indicators (*FBEN1–FBEN3*) and referred to environmental benefits of using CO₂-based fuels for aviation. Additionally, the HOC had three single-indicator LOCs: *Future of Flying (FBEN4)* referred to the possibility of continuing flying after fossil resources have been exhausted; *Sustainability Aviation (FBEN5)* referred to the product's potential to do something to increase the sustainability of air travel; and *Increased Quality (FBEN6)* referred to the increased quality of the product because of the use of CO₂.

Finally, the HOC *Barriers CO₂-Based Fuels* consisted of five single-indicator LOCs. Three of these are self-explanatory: *Increased Prices Air Tickets (FBAR1)*, *Insufficient Research (FBAR3)*, and *Decreased Quality (FBAR5)*. Moreover, *Safety Risk (FBAR2)* referred to the fear that the fuels pose a safety risk because existing motors were not built for them, and *Less Motivation to Fly Less (FBAR4)* referred to the fear that people will be less motivated to change their flying behavior for environmental reasons when the CO₂-based fuels are used.

The final construct, which was a HOC as well, regarded the acceptance of CO₂-based fuels for aviation. In line with the used definition of acceptance (**Section 3**), it referred to people's willingness to use, support, and prefer the product. *Acceptance CO₂-Based Fuels* consisted of three LOCs and resembled a formative measurement, since including other acceptance aspects likely changes the construct. The items for the indicators of the LOCs were presented as a Likert scale question. The first was a single-indicator LOC *Willingness to Use (FCA1)*, more specifically this referred to the respondents' willingness to fly in an airplane driven by CO₂-based fuels. Moreover, the LOC *Support* consisted of two indicators (*FCA2, FCA3*) and referred to the respondents' support of CO₂-based fuels for air travel. *Support* resembled a reflective measurement, since one either supports the product or not, and it is thus an overlying construct for its indicators. For the same reason, the final LOC, *Preference*, also resembled a reflective measurement. It consisted of three indicators (*FCA4–FCA6*) and referred to the respondents' preference of CO₂-based fuels compared to conventional options.

6.4.3 Model Evaluation

The model was implemented and evaluated using the programming language *R* and the *SEMinR* package⁸ (Ray et al., 2021). With $N = 2,187$ respondents, the sample was large enough to be used for our hypothesized model (**Section 6.4.2**) (Hair et al., 2017, p. 47). During the analysis, we refined the hypothesized model through several iterations to find a final model with a good quality. To do so, we first refined the measurement model through the step-wise removal of indicators that did not adhere to the quality criteria, removing

the worst one in each iteration. When the measurement model sufficed, the structural model was evaluated and refined by removing the worst relationship that did not meet the quality criteria in each iteration, until the structural model sufficed as well. In **Section 7**, we only outlined the results for the final model. To evaluate the measurement model, different quality criteria were used for formative and reflective measurements. Since all HOCs were formative, their quality was evaluated using the criteria for formative measurements. The quality of the HOCs' LOCs was evaluated separately based on their measurement type (Sarstedt et al., 2019). Moreover, there are no quality criteria for single-indicator constructs. Finally, we applied bootstrapping with 5,000 repetitions to the model. This was done to be able to assess several quality criteria that use the bootstrapped confidence interval (*CI*).

Reflective measurement evaluation. We reported the loadings (λ) and assessed the internal consistency reliability, convergent reliability, and discriminant validity according to the guidelines by (Hair et al., 2017, p. 136–143). The *internal consistency reliability* refers to how well the different indicators fit together. To assess this we reported Cronbach's alpha (α) as the lower bound of the true reliability and the composite reliability (ρ_C) as the upper bound. To meet the criterion, both the values had to be ≥ 0.60 and ≤ 0.90 . The *convergent reliability* considers “the extent to which a measure correlates positively with alternative measures of the same construct” (Hair et al., 2017, p. 137). To measure this, we considered the average variance extracted (AVE) and the outer indicator loadings. When $AVE \geq 0.50$ and $\lambda \geq 0.70$ there was convergent reliability. The *discriminant validity* is “the extent to which a construct is truly distinct from other constructs by empirical standards” (Hair et al., 2017, p. 138). This was measured using the heterotrait-monotrait ratio (HTMT) by assessing the bootstrapped *CI*s. If the *CI*s did *not* contain the value 1, there was sufficient discriminant validity.

Formative measurement evaluation. We reported the original estimate weight (w) and the mean weight of the bootstrapping (M). As quality measures, we assessed the collinearity, as well as the significance and relevance of the indicators according to the guidelines by Hair et al. (2017, p. 163–175). We could not assess the convergent validity—“the extent to which a measure correlates positively with other (e.g., reflective) measures of the same construct using different indicators”—since we did not measure the same constructs in multiple ways. *Collinearity* refers to whether indicators of the same construct highly correlate. For formative measurements, indicators are expected not to show collinearity. This was assessed using the variance inflation factor (VIF), which showed that there was no collinearity if $VIF \leq 5$. For the *significance and relevance* of the indicators, the outer weight (w) was evaluated. A positive w signifies relevance. The significance of the weight was assessed using the t-statistic of the two-tailed t-test, which had to be $t > 1.65$. Additionally, significance was implied if the bootstrapping *CI* did not contain 0.

Structural model evaluation. The evaluation of the structural model was also conducted based on the guidelines by Hair et al. (2017, p. 205–215). For each relationship, we reported the

⁸<https://CRAN.R-project.org/package=seminr>.

original estimate β and the bootstrapped mean estimate M . The β value refers to the strength of the relationship: if the exogenous construct changes by x , the endogenous construct changes by $x \times \beta$. We first assessed the *collinearity* of each endogenous construct with multiple exogenous constructs pointing toward it using the VIF. There was no collinearity if $VIF \leq 5$. Then, we evaluated the *significance* of the relationships using the t-statistic of the two-tailed t-test and the bootstrapped CI. A relationship was significant if $t > 1.65$ — p was reported as well—and CI did not contain 0. To see whether the impact of an exogenous construct on an endogenous construct was substantial, the *effect size* f^2 was calculated and interpreted as follows: $f^2 = 0.02$ (small effect), $f^2 = 0.15$ (medium effect), $f^2 = 0.35$ (large effect). Finally, we looked at the *in-sample predictive power* of the constructs using R^2 and R^2_{adj} which were interpreted as follows: $R^2 \leq 0.10$ (lack of predictive power), $R^2 = 0.25$ (weak power), $R^2 = 0.50$ (moderate power), $R^2 = 0.75$ (substantial power).

6.5 Additional Statistical Analyses

To get an idea of how the constructs used in the PLS-SEM model were evaluated, we additionally analyzed them separately. To do so, we computed a value for the constructs by taking the mean of its indicators in the final model. For the HOCs, we used the LOC's single indicators and did not separately consider the LOCs. For all of these constructs, Cronbach's was $\alpha \geq 0.70$ (Supplementary Table S1 in the supplementary material). As descriptive statistics, we reported the sample's mean evaluation (M) and standard deviation (SD). To test whether the mean evaluation was significantly different from the midpoint of the scale—which lay at 2.5—we used one sample t-tests. An evaluation significantly higher than the midpoint of the scale indicated a significant tendency toward the positive. There were no evaluations lower than the midpoint of the scale. We also used paired samples t-tests to test whether the single adjective pairs of the affective evaluation of CCU and CO₂-based fuels were evaluated significantly different⁹. For both of these tests, the level of significance was set at $\alpha = 0.05$ and Cohen's d was calculated as the effect size. The latter was interpreted as follows: $d = 0.20$ (small effect), $d = 0.50$ (medium effect), and $d = 0.80$ (large effect) (Cohen 1988, 1992, as cited in Field, 2018, p. 176).

7 RESULTS

In this section we will describe the respondents' evaluation of CCU and CO₂-based fuels for aviation, the results of the final model based on PLS-SEM, and the final model compared to the hypothesized model. Additionally, we will take a look at the strength of the predictions and predictors.

⁹Before conducting paired t-tests it was checked if assumptions are met and normal distribution was present. In case of sporadic outliers we additionally checked whether nonparametric testing yielded same significance and since this was the case we stayed with the interpretation of these results.

TABLE 1 | Descriptive statistics and results of one sample t-test with 2.5 for the evaluation of the constructs for CCU and CO₂-based fuels.

	<i>M</i>	<i>SD</i>	<i>t</i> (2,186)	<i>p</i>	<i>d</i>
Acceptance CO ₂ -based fuels	3.22	0.89	37.6	<0.001	0.80
Benefits CO ₂ -based fuels	3.30	0.84	44.6	<0.001	0.95
Barriers CO ₂ -based fuels	2.63	0.90	6.88	<0.001	0.15
Affective evaluation CO ₂ -based fuels	3.18	1.08	29.2	<0.001	0.62
Benefits CCU	3.10	0.83	33.9	<0.001	0.72
Barriers CCU	2.70	0.78	9.28	<0.001	0.20
Affective evaluation CCU	2.96	1.05	20.4	<0.001	0.44

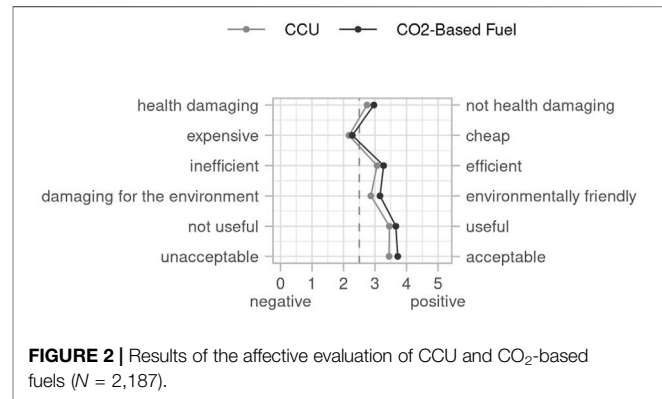


FIGURE 2 | Results of the affective evaluation of CCU and CO₂-based fuels ($N = 2,187$).

7.1 Evaluation of Carbon Capture and Utilization and CO₂-Based Fuels

Table 1 depicts the results of the paired-samples t-tests with the midpoint of the scale for the constructs. It shows that the respondents accepted the use of CO₂-based fuels rather than rejecting it, agreed to the perception of the fuels' benefits, as well as the perception of its barriers. For the perception of CCU as a production method, both the benefits and the barriers were also perceived rather than not. Regarding the perception of both CCU and the fuel, the effect size for the difference between the evaluation and the midpoint of the scale was negligible and small, respectively, for the barrier perception, but large and medium, respectively, for the benefit perception.

The table also includes the affective evaluation of CCU and the fuels. These evaluations can directly be compared since the same adjective pairs were used in both semantic differentials. On average, the affective evaluation tended toward the positive for both CCU and the fuels. In Figure 2, the evaluations of the single adjective pairs for CCU and the fuels are depicted. For all adjective pairs, CO₂-based fuels were evaluated a bit more positively than CCU, and all of these differences were significant (Table 2).

7.2 Partial Least Squares Structural Equation Modeling—Model Evaluation

7.2.1 Measurement Model Evaluation

The results for the reflective LOCs are depicted in Table 3. They show that the convergent validity and internal consistency

TABLE 2 | Results of paired samples t-test for differences in the affective evaluation of CCU and CO₂-based fuels.

	CCU		CO ₂ -based fuels		<i>t</i> (2,186)	<i>p</i>	<i>d</i>
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>			
Unacceptable–acceptable	3.45	1.34	3.72	1.28	−10.9	<0.001	−0.21
Not useful–useful	3.46	1.38	3.66	1.32	−7.83	<0.001	−0.15
Damaging for the environment–environmentally friendly	2.87	1.53	3.16	1.38	−9.45	<0.001	−0.20
Inefficient–efficient	3.07	1.30	3.27	1.32	−7.59	<0.001	−0.16
Expensive–cheap	2.17	1.28	2.28	1.36	−3.72	<0.001	−0.079
Health damaging–not health damaging	2.75	1.38	3.00	1.30	−7.93	<0.001	−0.16

TABLE 3 | Evaluation of the reflective lower-order constructs (LOC): original estimate loading (λ), internal consistency reliability (α , ρ_c), and convergent validity (AVE).

Construct	Indicator	λ	α	ρ_c	AVE
Acceptance of CO ₂ -based fuels: support	FCA2	0.89	0.67	0.86	0.75
	FCA3	0.84			
Acceptance of CO ₂ -based fuels: preference	FCA4	0.87	0.79	0.88	0.70
	FCA5	0.85			
	FCA6	0.79			

TABLE 4 | Evaluation of the formative constructs and lower-order constructs (LOC): collinearity (VIF) and indicator weight (original estimate *w*, bootstrap mean *M*, t-statistic *t* (2,187), *p*-value).

Construct	Indicator	VIF	Weights			
			<i>w</i>	<i>M</i>	<i>t</i> (2,187)	<i>p</i>
Benefits CCU: environmental benefits CCU	CUBEN1	2.28	0.22	0.22	5.74	<0.001
	CUBEN2	2.09	0.29	0.29	7.70	<0.001
	CUBEN3	1.81	0.16	0.16	4.15	<0.001
	CUBEN4	2.44	0.26	0.26	6.38	<0.001
	CUBEN5	2.17	0.27	0.27	6.90	<0.001
Benefits CCU: policy benefits	CUBEN6	1.78	0.20	0.20	5.03	<0.001
	CUBEN7	1.67	0.51	0.51	14.6	<0.001
	CUBEN8	1.88	0.31	0.31	8.24	<0.001
	CUBEN9	1.55	0.21	0.21	6.25	<0.001
Barriers CCU: policy barriers	CUBAR1	1.31	0.20	0.20	3.63	<0.001
	CUBAR2	1.44	0.36	0.36	6.37	<0.001
	CUBAR3	1.32	0.45	0.45	8.56	<0.001
	CUBAR4	1.22	0.35	0.35	6.49	<0.001
Barriers CCU: sustainability barriers	CUBAR5	1.38	0.36	0.36	5.30	<0.001
	CUBAR6	1.46	0.39	0.39	6.30	<0.001
	CUBAR7	1.37	0.32	0.32	5.08	<0.001
	CUBAR8	1.29	0.27	0.27	4.46	<0.001
Affective evaluation CCU	CUAE1	3.62	0.23	0.23	4.92	<0.001
	CUAE2	3.53	0.28	0.28	6.42	<0.001
	CUAE3	2.97	0.15	0.15	3.46	<0.001
	CUAE4	1.82	0.25	0.25	7.27	<0.001
	CUAE5	1.19	0.16	0.16	5.34	<0.001
	CUAE6	2.40	0.22	0.21	5.75	<0.001
Benefits CO ₂ -based fuels: environmental benefits fuels	FBEN1	2.11	0.51	0.51	15.6	<0.001
	FBEN2	1.92	0.29	0.29	8.66	<0.001
	FBEN3	1.88	0.34	0.34	10.5	<0.001
Affective evaluation CO ₂ -based fuels	FAE1	4.97	0.26	0.26	5.75	<0.001
	FAE2	5.32	0.34	0.34	7.34	<0.001
	FAE3	3.36	0.11	0.11	3.05	= 0.001
	FAE4	2.67	0.16	0.16	4.37	<0.001
	FAE5	1.40	0.13	0.13	4.74	<0.001
	FAE6	2.76	0.19	0.19	5.61	<0.001

TABLE 5 | Evaluation of the formative higher-order constructs (HOC) based on its lower-order constructs (LOC): collinearity (VIF) and indicator weight (original estimate *w*, bootstrap mean *M*, t-statistic *t* (2,187), *p*-value).

HOC	LOC	VIF	Weights			
			<i>w</i>	<i>M</i>	<i>t</i> (2,187)	<i>p</i>
Benefits CCU	Environmental benefits CCU	3.80	0.64	0.64	14.1	<0.001
	Policy benefits	3.49	0.22	0.22	4.77	<0.001
	Employment opportunities	1.56	0.097	0.097	3.26	= 0.001
	Raise awareness use of CO ₂	2.23	0.14	0.14	3.80	<0.001
Barriers CCU	Policy barriers	2.18	0.75	0.75	12.6	<0.001
	Sustainability barriers	2.18	0.31	0.32	4.61	<0.001
Benefits CO ₂ -based fuels	Environmental benefits fuels	2.43	0.64	0.64	21.0	<0.001
	Future of flying	1.62	0.12	0.12	4.30	<0.001
	Sustainability aviation	2.06	0.28	0.28	9.95	<0.001
	Increased quality	1.15	0.15	0.14	6.13	<0.001
Barriers CO ₂ -based fuels	Safety risk	1.49	0.53	0.52	8.82	<0.001
	Insufficient research	1.28	0.20	0.20	3.11	= 0.001
	Decreased quality	1.37	0.50	0.50	8.96	<0.001
Acceptance CO ₂ -based fuels	Willingness to use	1.95	0.12	0.12	4.22	<0.001
	Support	1.79	0.58	0.58	19.9	<0.001
	Preference	1.79	0.45	0.45	14.3	<0.001

reliability were granted. The discriminant validity of these measurements was also established, since none of the *CI*'s for the indicators contained 1. The results for the formative constructs and LOCs are depicted in **Table 4** and show that for most constructs the indicators did not show collinearity. Only for the *FAE2* of *Affective Evaluation CO₂-Based Fuels* the VIF >5. This indicator was nevertheless included in the final model to keep the indicators of this construct similar to the ones for *Affective Evaluation CCU*. To control for the effect of this procedure, and checking if the less restrictive handling of the VIF in this item is decisive for the overall model, an alternative analysis was run in which this indicator was discarded. Owing to the fact that the differences in rounding to the second decimal place produced little to no differences for the interpretation of relevant values in the model evaluation, *FAE2* was retained for modeling in favor of a basis of comparison in the measurement of the affective component of the model. Moreover, the results in the table reveal that all indicators were significant and relevant for their constructs based on their positive and significant weights. Additionally, the *CI*'s for all indicators did not contain 0, which also indicated their significance.

Finally, the results of the formative HOCs are depicted in **Table 5**. None of the LOCs showed collinearity. They were also all significant and relevant for the HOCs based on their positive and significant weights, as well as the *CI*'s that did not contain 0.

Overall, the measurement model thus sufficiently met the quality criteria. In the next step, the structural model was evaluated.

7.2.2 Structural Model Evaluation

The results of the structural model evaluation can be found in **Table 6**. The table shows that there was no collinearity in the model. All path coefficients were significant based on the

t-statistic and the *CI*s not containing 0. The effect of five relationships was small, of four medium, and of the final two large.

The in-sample predictive power was very weak for *Barriers CCU* ($R^2 = 0.13$) and *Barriers CO₂-Based Fuels* ($R^2 = 0.17$). For *Benefits CCU* ($R^2 = 0.30$) and *Affective Evaluation CO₂-Based Fuels* ($R^2 = 0.45$) it was weak. And finally, for *Benefits CO₂-Based Fuels* ($R^2 = 0.56$) and *Acceptance CO₂-Based Fuels* ($R^2 = 0.57$) the in-sample predictive power was moderate (Hair et al., 2018).

7.3 Complete Model: Hypotheses Validation

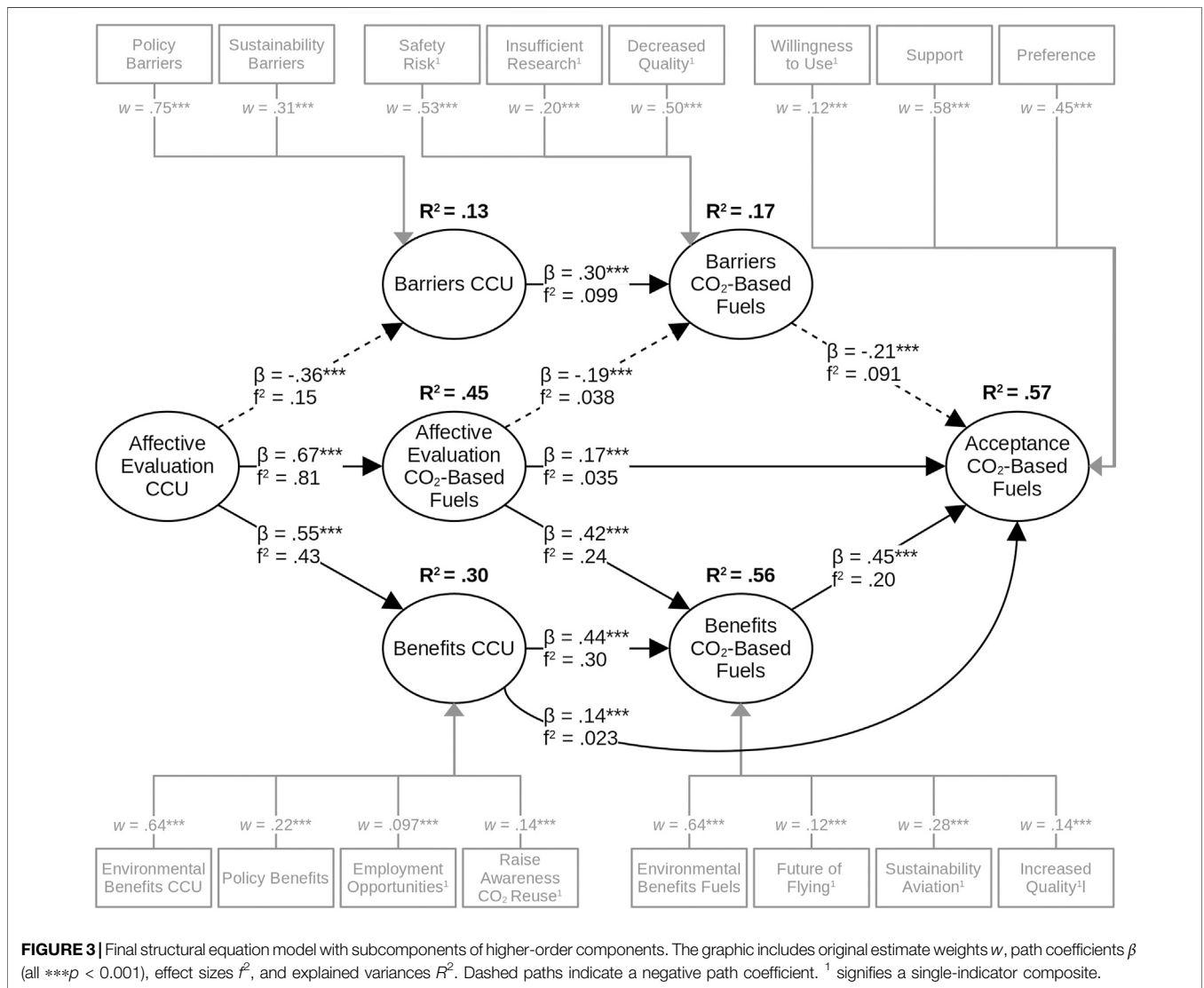
Through nine iterations we converted our hypothesized model (**Section 6.4.2**) into a model that sufficiently fulfilled the quality criteria (**Section 7.2**). The final model is depicted in **Figure 3**. In this graphic, the LOCs that serve as indicators for the HOCs are included (gray rectangles) besides the HOCs in the structural model (black ovals). The single indicators for the non-HOCs and LOCs are not represented in the graphic, but can be found in the supplementary material. Compared to the hypothesized model, several single-indicator LOCs were removed from the final model because they were not significant for the respective HOC: *Scale Barrier* of the HOC *Barriers CCU*, as well as *Increased Prices Air Tickets* and *Less Motivation to Fly Less* of the HOC *Barriers CO₂-Based Benefits*.

The hypotheses were evaluated by comparing the hypothesized structural model (**Figure 1**) to the structural model of the final model (**Figure 3**). In these graphics, relationships are represented by a path from the exogenous to the endogenous construct.

First, we looked at the direct relationships from the perception to the acceptance of CO₂-based fuels for aviation (H_1). Only for the barriers of CCU ($H_{1,d}$) we found no significant relationship. The benefits of CO₂-based fuels ($H_{1,a}$) and the benefits of CCU

TABLE 6 | Evaluation of the structural model: path coefficient evaluation [original estimate β , bootstrapped mean M , confidence interval (CI), t-test statistic $t(2,187)$, and significance (p)], effect size (f^2), and collinearity (VIF).

Exogenous construct	Endogenous construct	Path coefficient					f^2	VIF	
		β	M	CI		$t(2,187)$			p
				2.5%	97.5%				
Barriers CO ₂ -based fuels	Acceptance CO ₂ -based fuels	-0.21	-0.21	-0.24	-0.17	11.6	<0.001	0.091	1.10
Benefits CO ₂ -based fuels	Acceptance CO ₂ -based fuels	0.45	0.45	0.40	0.50	18.6	<0.001	0.20	2.27
Affective evaluation CCU	Affective evaluation CO ₂ -based fuels	0.67	0.67	0.64	0.70	41.0	<0.001	0.81	—
Affective evaluation CCU	Barriers CCU	-0.36	-0.37	-0.41	-0.32	15.8	<0.001	0.15	—
Affective evaluation CCU	Benefits CCU	0.55	0.55	0.51	0.59	27.6	<0.001	0.43	—
Affective evaluation CO ₂ -based fuels	Barriers CO ₂ -based fuels	-0.19	-0.19	-0.24	-0.14	7.64	<0.001	0.038	1.14
Affective evaluation CO ₂ -based fuels	Benefits CO ₂ -based fuels	0.42	0.42	0.37	0.46	17.6	<0.001	0.24	1.42
Affective evaluation CO ₂ -based fuels	Acceptance CO ₂ -based fuels	0.17	0.17	0.12	0.22	7.01	<0.001	0.035	1.90
Barriers CCU	Barriers CO ₂ -based fuels	0.30	0.31	0.26	0.36	12.1	<0.001	0.099	1.14
Benefits CCU	Benefits CO ₂ -based fuels	0.44	0.44	0.39	0.48	18.8	<0.001	0.30	1.42
Benefits CCU	Acceptance CO ₂ -based fuels	0.14	0.14	0.090	0.18	5.69	<0.001	0.023	1.86



(H_{1c}) were positively related to the acceptance, and the barriers of CO₂-based fuels (H_{1b}) were negatively related to the acceptance.

Second, we considered the relationships from the perception of CCU to the perception of CO₂-based fuels (H_2). We found significant positive relationship between the perceptions of benefits of CCU and CO₂-based fuels (H_{2a}) and between the perceptions of barriers of CCU and CO₂-based fuels (H_{2c}). Between the benefits of CCU and the barriers of CO₂-based fuels (H_{2b}) and vice versa (H_{2d}) we found no significant relationships.

Subsequently, the relationships from the affective evaluations to the perception and acceptance were evaluated (H_3). The affective evaluation of CO₂-based fuels was positively related to the acceptance of the fuels (H_{3a}), but the affective evaluation of CCU was not significantly directly related to the acceptance (H_{3d}). Moreover, the affective evaluation of CO₂-based fuels was positively related to the benefits of the fuels (H_{3b}) and negatively related to its barriers (H_{3c}). Similarly, positive and negative relationships were found between the affective evaluation of CCU and the benefits (H_{3e}) and barriers (H_{3f}) of CCU, respectively.

The last hypotheses to consider were the relationships from the affective evaluation of CCU to the affective evaluation and perception of CO₂-based fuels (H_4). We found no direct significant relationship between the affective evaluation of CCU and the benefits (H_{4b}) and barriers (H_{4c}) of CO₂-based fuels. However, there was a significant positive relationship between the affective evaluation of CCU and the affective evaluation of CO₂-based fuels (H_{4a}).

Finally we looked at the strength of the predictions and predictors. As aforementioned, we found a moderate in-sample predictive power for the acceptance of CO₂-based fuels. The relationship with the benefits of CO₂-based fuels was thereby most relevant. This was followed by the barrier perception and affective evaluation of the fuels, and finally the benefit perception of CCU. For predicting the benefits of CO₂-based fuels—with a moderate in-sample predictive power—the benefits of CCU were most relevant, closely followed by the affective evaluation of the fuels. For the barriers of CO₂-based fuels—with a weak in-sample predictive power—the barriers of CCU were also most relevant followed by the affective evaluation of the fuels, but the gap between the strength of both predictors was larger. The affective evaluation of CCU was the only predictor for the barriers of CCU, the benefits of CCU, and the affective evaluation of CO₂-based fuels in the model. It is thereby noteworthy that this single predictor resulted in a moderate in-sample predictive power for the affective evaluation of the fuels.

8 DISCUSSION

In the short term, merely trying to limit CO₂-emissions will likely not suffice to mitigate climate change (Peters and Geden, 2017). It is therefore important that circular economy approaches—for which Carbon Capture and Utilization (CCU) is a cornerstone, which reuse (otherwise) emitted CO₂, are developed and adopted

as well. A prerequisite for the successful roll-out of CCU is its social acceptance, which includes the public's acceptance of CCU products.

In this study, we focused on the acceptance of one such product: CO₂-based fuels for aviation. To our knowledge, the study was the first to aim at gaining a better understanding of the role the evaluation of CCU as a production method plays on the acceptance of a CCU product. We applied a quantitative approach integrating a large European sample. We used partial least squares structural equation modeling for our exploratory research aim because it allowed us to evaluate a large number of variables simultaneously, thereby considering the relationships between these latent variables and also the quality of the latent variables themselves.

The present study yielded a better understanding of how the acceptance of CO₂-based fuels is formed. Based on this knowledge, this final section answers the study's research question: **What role, if any, does the evaluation of CCU as a production method play in the formation of the acceptance of CO₂-based fuels for aviation as an example of a CCU product?** Additionally, the knowledge is used to formulate guidelines for the development of communication and information strategies. Finally, we reflect on the study's limitations and resulting future research prospects.

8.1 The Role of the Cognitive Evaluation of Barrier and Benefit Perceptions on Acceptance Evaluations

First, we considered the role of the cognitive evaluation, in the form of the perceived benefits and barriers of CCU and CO₂-based fuels, for the acceptance of the product. Generally, the fuels were accepted, but not strongly yet. This is in line with previous findings on the acceptance of this (Engelmann et al., 2020), and other CCU product(s) (Offermann-van Heek et al., 2018). For both the fuels and CCU, the benefits were perceived, and a higher benefit perception was related to a higher acceptance of CO₂-based fuels. The relationship between the benefits of a CCU product and the acceptance of this product is in line with previous research (e.g., Huijts et al., 2012; Offermann-van Heek et al., 2018). However, the role of the benefits of CCU for the acceptance evaluation of the CCU product is a new insight. The benefits of CCU only have a weak direct affect on the acceptance compared with the other acceptance predictors. However, they are also indirectly related to the acceptance of the fuels through their direct relationship with the benefits of the fuels. For both benefit perceptions, the environment-related benefits played a substantial role, confirming previous findings (Offermann-van Heek et al., 2018; Arning et al., 2021).

The barriers of CCU and CO₂-based fuels were perceived as well. However, the barrier perceptions were less pronounced in comparison with the perceived benefits (as taken from the descriptive statistics and the lower effect sizes of perceived barriers of both product and technology). Perceived barriers had a moderating effect on acceptance through the direct positive relationship with the barriers of the product. The stronger the barriers for CO₂-based fuels are perceived, the

lower the acceptance of the product. Moreover, it is noteworthy that compared to the previously identified lack of sustainability of CCU as a relevant barrier (Jones et al., 2014; Arning et al., 2017), barriers related to lacking policy seemed to be more important for the model. This reflects laypeople's policy expectations and addresses the need for the informed formation of policies for CCU (Moreau et al., 2017; Hartley et al., 2020). The barriers for the fuels highlighted safety concerns as well as doubts concerning reductions in product quality. This allows us to speculate about the relationship between the barriers of CCU and the product. An increased questioning of appropriate policy strategies may be accompanied by doubts about the characteristics of the end product.

Moreover, the benefits of CCU do not seem to influence the barriers of CO₂-based fuels and vice versa. This can be seen as empirical evidence that benefit perception and barrier perception are not inversely related and do not exclude each other. Instead, consumers see both positive and negative aspects of CO₂-based fuels for aviation simultaneously. This phenomenon of perceiving both sides (in varying weights) to some extent is quite typical for the evaluation of technical innovations and acceptance (e.g., Huijts et al., 2019; Offermann-van Heek et al., 2018). In the adoption process, consumers see the benefits and the barriers on different levels—in terms of personal and societal consequences—and weigh both. This results in the acceptance decision.

8.2 The Role of the Affective Evaluation on Acceptance Evaluations

Besides the cognitive evaluation of a product or technology, to be able to explain the acceptance, it is important to also consider the public's affective evaluation of the product or technology (Finucane et al., 2000). The affective evaluations of CCU and CO₂-based fuels were both positive on average. However, for all included adjective pairs, the fuels were evaluated more positively than CCU although small effect sizes have to be taken into account. This confirms previous findings that found the end product to be viewed more positively than the necessary production steps (Offermann-van Heek et al., 2020). For the present study this means that the fuel is perceived to be less health-damaging and more cheap, efficient, environmentally friendly, useful, and acceptable than CCU as the technology used to make the fuel. One possible explanation is a lack of understanding of the technology as opposed to a perceived understanding of the fuel as a product. Even though climate change is increasingly recognized as an (environmental) threat, it can still be difficult to understand complex technological approaches aimed at mitigating climate change, such as CCU. This, in turn, can create uncertainty when assessing the benefits or risks of the technology. In contrast, CO₂-based fuels—which laypeople have also not been able to experience yet—replace known, conventionally used, and well-established products such as kerosene. Fuels in general are thus more tangible and laypeople might have been able to more easily assess and evaluate their use.

The affective evaluation of CO₂-based fuels was directly related to the acceptance of the product, and also acted as a

mediator through relationships with its benefit and barrier perception. The higher the affective evaluation, the higher the acceptance. The affective evaluation of CCU was not directly related to the acceptance, nor to the benefit and barrier perception of the product. However, it was related to the benefit and barrier perception of CCU, as well as the affective evaluation of the fuels. Indirectly, an increased positive affective evaluation of CCU is thus still related to an increased acceptance.

Despite the new perspective provided by the integration of both technology and product, the results of the model partially confirm previous research findings. The direct effect of the affective evaluation of the product on its acceptance is in line with previous findings for CCU as a technological approach, for which Linzenich et al. (2019b) found that affect in the form of risk perceptions directly influenced its acceptance. Interestingly, Liu et al. (2019) differentiated between positive and negative affects—which our measurement instrument did not due to the opposite polarity of the semantic differentials—when investigating their impact on the acceptance of self-driving vehicles: People's behavioral intention was only influenced by positive affect, whereas negative affect did not have a direct impact. Also a study by Arning et al. (2020) identified an effect of the positive affective evaluation on the acceptance of the CCU technology, but did not for the negative affect in terms of perceived threats.

Our model shows that besides the cognitive evaluation—which involves a rational weighing of advantages and disadvantages—affect is a central component in shaping the acceptance of CO₂-based fuels for aviation. As a new insight, we extended this knowledge by having identified the indirect effect of the affective technology evaluation on the product's acceptance.

8.3 Evaluation of Carbon Capture and Utilization and the Acceptance of CO₂-Based Fuels

To answer the research question: Overall we found that the evaluation of CCU as a production method was mostly indirectly related to the acceptance of the CO₂-based fuels through moderating effects through relationships with the evaluation of the fuels. The only exception was the benefit perception of CCU, which was directly related to the acceptance. However, relative to acceptance's relationship with the benefit and barrier perception and affective evaluation of the fuel, the direct relationship with acceptance was weak both in terms of β and effect size. We believe there are two possible explanations for the lack of a direct relationship between the evaluation of CCU and acceptance. First, respondents might have a harder time evaluating a complex unknown technology like CCU based on basic information alone and might therefore be more careful in their evaluation (Zaubrecher and Ziefle, 2016). It might be easier for them to evaluate a product that is said to be similar to products they are more familiar with. Therefore, the technology might be rather neglected when evaluating the product. This argument is stressed by the more positive affective evaluation of the fuel compared to CCU—which is in line with previous findings on perceptions of CCU and CO₂-

based fuels (Arning et al., 2021)—even though the fuel would not exist without the technology. Alternatively, consumers might generally care less about the production method of products, as long as the product itself has a good quality and is safe. Although a direct comparison between the relevance of production type and a resulting product from a lay perspective has not been drawn so far to our knowledge, assumptions can nevertheless be made from previous research. For the roll-out of a CCU plant, the perceived importance of technology attributes showed that, apart from the fact that CO₂ can be stored and thus fossil resources saved, aspects relating to the involvement of the public in planning or the type of plant operator had comparatively little to very little relevance (Arning et al., 2021). This indicates that laypeople focus on potential benefits of the production rather than on roll-out conditions that could directly affect them, e.g., in the form of citizen participation.

Even though the evaluation of the product was thus more important for the acceptance of CO₂-based fuels, the evaluation of CCU still played an indirect role as it had moderating effects through benefit and barrier perceptions as well as its affective component. The affective evaluation of CCU even seems to play a substantial role in predicting the affective evaluation of the fuels, since as its only predictor in the model it managed to explain 45% of the variance for this construct. Affective evaluations in energy technology acceptance are known to considerably impact social acceptance (Slovic et al., 1982; Huijts et al., 2012; Huijts, 2018), especially in the beginning of the innovation management process when people do not have much familiarity with the technology and cannot yet assess the adverse and long-term consequences of development on them (Midden and Huijts, 2009; Bögel et al., 2018). Thus, affective responses give valuable insights into “archaic” reactions to uncertainty and unknown consequences connected to technical innovations and related transformation processes (Renn et al., 2011), especially in the early phase of the production process.

8.4 Insights for Communication and Information Strategies and Managerial Recommendations

The strategy for the public communication resulting from the insights of the study can be divided into a general and specific level.

At a *general* level, the successful implementation of changes in the energy transition will deeply affect social processes and needs societal support. Therefore, the transition and roll-out of energy technology innovations requires a carefully planned and systematically implemented communication. This allows the early identification of acceptance conflicts and controversial perspectives of the involved parties and enables their resolution through discourse (Drews and Van den Bergh, 2016). Communication strategies should closely reflect the perceptions and acceptance of the public (Offermann-van Heek et al., 2018; Kluge et al., 2021). Since acceptance decisions for technical innovations typically simultaneously consider the perceived benefits and barriers, both the advantages and potential drawbacks should be communicated transparently (Offermann-van Heek et al., 2018; Linzenich et al., 2019b). Not doing so, and instead

predominately reporting the obvious advantages—as might be recommended by marketing approaches—can lead to public distrust in authorities as well as distrust in the technology, product, and perceived honesty of information providers. This happens whenever the public feels that information is being concealed. Especially industry and politics for which the public tends to assume other predominant motives for innovation—e.g., market claims, economic benefits, or election-related motives—instead of truly supporting a sustainable energy supply, are viable for such mistrust (Offermann-van Heek et al., 2018; Linzenich et al., 2019b).

On a more *specific* level, relating to the outcomes of the present study, not only the product features of CO₂-based fuels need to be addressed in public communication strategies, but also the production process. Even though the direct relationship between process-related components and product acceptance was not very strong, it still played a substantial indirect role. It could thus be shown that focusing exclusively on end-consumption in the form of the fuel as a product would disregard elementary aspects—in this case the technological production approach—when informing the public. Without including the production approach, one would miss out on empowering the public with appropriate information (about advantages and disadvantages) for informed participation (e.g., in the form of adapted consumption and travel behavior), which is becoming increasingly important in times of the ever more urgent pursuit of reaching the 1.5°C target. Also with regard to the acceptance of other goods that could be produced in a circular economy fashion, communication about the technical possibilities and pathways is of significant importance. Laypeople, of course, do not have the same competence as technical experts, which allows them to understand all the technical details. The communication therefore has to follow a clear strategy aimed at generating tailored understandable information for differing individual information needs for both, aspects of product and production as well as the impact and importance of circular economy approaches. This could be especially important for the perception of potential barriers. Compared to the perceived benefits of CCU and CO₂-based fuels, the barriers were perceived less strongly, which indicates that general acceptance is unlikely to be hindered by major adoption obstacles. However, we have to acknowledge that the barriers were still somewhat perceived— $M = 2.70$ for CCU and $M = 2.63$ for CO₂-based fuels, out of the maximum of second 5.00 second, and that their influence was strong enough to be included in the model. If specific groups of consumers perceive the barriers more strongly, this could increase their effect on acceptance for these consumers. In general, but especially for these groups, the barriers should thus be included in communication strategies. In the model, policy and sustainability barriers were included for CCU, i.e., doubts about the policies for CCU and environmental sustainability of the technology. For the CO₂-based fuels for aviation as a CCU product, safety risks and the possibly decreased quality of the novel fuel seemed to be important barriers. Stressing the whole picture of the technical approach and the innovation would thus help not only to deliver the impact of each step in the technology process and their relation to the

overall goal to reduce climate-related goals, but also to provide transparency with respect to the technology innovation that is needed by the public to support climate-related measures. Last but not the least an open communication policy is essential for the public that they are taken seriously and involved.

At this moment, informing the public and communicating a technological innovation usually follows a top-down approach. The solution to preventing the anticipated or feared resistance toward, and boycott of, the product seems to be to quite superficially and nontransparently inform the public at the end of the development process. This approach possibly seems to be the simplest and most effective, especially since the lay public, naturally, does not have the expertise to adequately evaluate the technical processes. From a technical expert point of view, it might probably be the most obvious and convenient to assume that if the public is not confronted with the possible disadvantages, they will not even think of rejecting the product or technology. However, in the long term, such “hiding” communication strategies will not be successful and fall short. This is not only explained by lacking honesty toward, and consideration of the information needs of, the public and the resulting uninformedness perceived by the public, as well as their feeling of being kept out of the loop. More so, it neglects that (non-)acceptance reactions in the population often reflect decision conflicts between societal goals, local impacts, and individual motives (Evans et al., 2013; Feinberg and Willer, 2013). Those decision conflicts reach deep into a person’s identity and touch their daily living circumstances. For that reason, it must be assumed that they do not simply disappear over time.

Laypeople—this group does include not only the broader public, but also policy and decision makers on different levels and in different organizations—are unlikely to engage with the product if they do not have the opportunity to familiarize themselves with the product, the technology, and its societal benefits, or if they feel like they are not being adequately considered and assume that there is not enough transparency to allow them to get familiar with the idea, and the consequences of the innovation. Therefore, open information is an inevitable precondition of a successful roll-out (Brunsting et al., 2013; Götz and Wedderhoff, 2018; Arning et al., 2020) A balanced, honest, and trustful communication strategy is advisable. This should confirm the already positively experienced aspects—e.g., environmental benefits and employment opportunities, but also discuss, recognize, or in the case of misconceptions, invalidate, the perceived barriers. From a managerial perspective, it seems to be a timely issue of outstanding importance to systematically inform research, applications, governance, and policy to support the circular economy approach and to claim the area-wide economic and ecological necessity to rethink technology processes and products in line with circular economy activities and sustainable innovations.

8.5 Limitations and Future Research

Finally, we considered which further potential limitations of the study should be picked up in further research. Several key-points that related to different theoretical, empirical, and methodological issues were identified.

Considering construct ambiguity. First, we were not able to validate the convergent validity of the formative constructs. Future studies should aim to validate these quality criteria by implementing reflective measures measuring the same construct in the measurement instrument (Hair et al., 2017). However, more importantly, constructs are never a perfect representation of the latent variables they aim to represent. Instead, they should be seen as an approximation of these latent variables (Sarstedt et al., 2016). In addition, by definition, formative constructs do not necessarily cover the entire latent variable but rather aspects of the variable. The use of other benefits, barriers, and adjective pairs thus likely changes the constructs. Since the items used were based on extensive literature study and discussions with experts, we do believe in their validity for CCU and CO₂-based fuels. A crucial issue in such explorative studies is the development and selection of appropriate items with a good item quality. However, especially in such novel fields, there are not always already validated items that can be used for the acceptance evaluation and the PLS-SEM modeling. In the present study, we therefore pursued a mixture out of an exploratory and validated approach. On the one hand, we developed items that reflected content coming from the exchange with technical experts; on the other hand, we reused items that have been extracted from previous (CCU) acceptance studies (Section 4) and validated scales that were available. Future studies should replicate the suitability and item quality of these items and should check if further items can be identified from qualitative research, which then should be included in the model to see whether it changes the relationships between the constructs. Additionally, social science studies on CCU (products) have consistently reported that the general public’s awareness of the technology is regrettably low (Offermann-van Heek et al., 2018; Linzenich et al., 2021). This can be attributed to the fact that, so far, no CCU product is available on the market and the population has thus not gotten the chance to gain hands-on experience. Future studies should track whether and how acceptance and perception outcomes change when this is possible, and more information becomes available.

Considering out-of-sample predictive power and causality. The identified model is only valid to explain the hypothesized relationships within our sample. Based on the used approach and analysis, the model’s out-of-sample predictive power cannot be granted. Moreover, because of the correlational nature of structural equation modeling, causal conclusions cannot be drawn based on this approach (Bullock et al., 1994). Although our model was valid to assess the hypotheses in the present study, future (experimental) studies should aim to validate the assumed predictiveness and causality the model conveys.

Considering single production steps. So far, we did not include the acceptance evaluations of the single production steps—i.e., separation, purification, transport, and conversion of CO₂—and compare them with, and relate them to, the acceptance evaluations for the product, CO₂-based fuels for aviation. Even though the SEM procedure yielded a first understanding of the role of the evaluation of the production process in the formation of acceptance for the product, it remains important to analyze the single steps separately. This will provide

insights into whether all the single steps of the circular economy approach are perceived, understood, and evaluated equally. Additionally, it could identify whether there are specific hurdles in the perception of the production steps that require additional communication efforts.

Considering local acceptance. In the present study, we addressed the public acceptance of CO₂-based fuels for aviation as an example of a CCU product, thereby touching aspects of the socio-political and market acceptance proposed by Wüstenhagen et al. (2007). However, any infrastructure for CCU plants is embedded in various land-use scenarios—i.e., the properties of the plant, its location, and its infrastructural needs—which need to be explored from a local perspective. Compared to the general public, the acceptance evaluations of those who personally experience proximity to the CCU plant could differ. The fears of people living in close proximity to the plant, as well as the perceptions of communal (local) decision makers who have to take into account inhabitants' voices, have to be considered. Future studies should aim to include local acceptance aspects in the model to be able to consider all dimensions simultaneously and gain a more complete view on the acceptance.

Considering user diversity and further acceptance drivers. The constructs in the model described in the present study had a low or moderate in-sample predictive power. This is likely the result of our focus on the role of the evaluation of CCU and CO₂-based fuels for explaining the acceptance of the product. We did not analyze demographic factors on acceptance yet and did also not include further (psychological) factors in our model (this would have exceeded the scope of the paper and also space restrictions). However, based on other acceptance models (Huijts et al., 2012) and the results of previous CCU acceptance studies (van Heek et al., 2017b; Offermann-van Heek et al., 2018; Arning et al., 2019) we know that these play an important role in explaining acceptance as well. Including user diversity factors—like *trust*, *innovativeness*, and *self-efficacy*—in future studies will increase the understanding of the acceptance of CO₂-based fuels. Additionally, it will help to explain what drives the perception and affective evaluation of CCU and the product, which our model showed play a substantial role in explaining acceptance ($R^2 = 0.57$). This knowledge helps to formulate targeted communication strategies for different consumer groups, and increase the likelihood of a successful market roll-out of the technology and product (Sovacool et al., 2018; Linzenich et al., 2019b; Liebe and Dobers, 2019). As part of this, we should also look into national differences. In our sample we included participants from four European countries—Spain, Norway, Germany, and Netherlands—but did so far not consider differences between these countries¹⁰. However, if research focuses on national acceptance differences, social and cultural norms and other diversity factors should be considered to explain the potential differences (Tellis et al., 2003; Zheng et al., 2021), since nationalities differ for myriad factors, e.g., socioeconomic

situation and familiarity with green energies. This will help to understand and address differences in culturally defined openness to innovation within, and across, European markets regarding CO₂-based fuels.

Considering further aspects of public communication. Even though the present study provided first insights into the aspects important for the communication of CO₂-based fuels for aviation, there may still be other important aspects for the successful communication of circular economy products and procedures. This should be explored empirically. As such, it needs to be studied which information—including type and depth of detail—on CO₂-based fuels is required. Additionally, it should be considered which information channels and media are preferred, and, more so, which media is trusted by the public in terms of reliability, actuality, and objectivity of the information. Altogether we should question which information instances are credible in the eyes of the public and which degree of complexity is tolerated by both the information providers and receivers (e.g., Offermann-van Heek et al., 2018; Kluge et al., 2021).

Considering further circular economy products and application fields. Finally, the findings at hand are only valid for the acceptance of CO₂-based fuels for aviation. The extent of the general validity of the results for other CO₂-based products, or circular economy approaches, remains unclear. It would be interesting for future studies to identify which acceptance factors are product specific, and which apply across different circular economy products. Whereas there might be universal acceptance principles—e.g., the fear of harm, economic burden, nature protection, personal comfort, and living standard, there might also be quite product-specific factors—e.g., proximity to the body of CCU products (van Heek et al., 2017a; Arning et al., 2018a) like CCU-based clothing, food packaging, or cosmetics. The consideration of different product categories as well as different technology routes in the production of CO₂-based goods in future studies would furthermore provide the opportunity to study tradeoffs between aspects such as production route and product.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethikkommission der Fachgruppe 7.3 “Empirische Humanwissenschaften” an der Philosophischen Fakultät der RWTH Aachen (Ethics Committee of the Division 7.3 “Empirical Human Sciences” at the Faculty of Arts and Humanities at RWTH Aachen). The participants provided their written informed consent to participate in this study.

¹⁰For a first glance into descriptive findings and differences across countries, a table can be found in the supplementary materials.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication. LS and LE were responsible for the methodology, conduction of the described study, data curation, validation of the data. KA conceptualized the empirical questionnaire study on which the SEM model was based. LS did the formal analysis and visualization. MZ was responsible for the funding acquisition and LE for the project management. LE, MZ, and LS did the final editing of the paper.

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SUPPLEMENTARY MATERIAL

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