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One step closer: Laypeople's perception of production steps for manufacturing CO_2-based jet fuel

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Abstract

Background The need for greenhouse gas abatement measures grows as climate change threatens life on earth. Negative emission technologies, such as carbon capture and utilization (CCU), can reduce emissions from the transport sector, particularly aviation. However, the lack of support and low public acceptance can impact the successful introduction of new technologies. This study analyzes the factors that influence acceptance of the single production steps (capture, purification, conversion, and transport of CO_2) of production of CO_2-based jet fuels to identify acceptance hot spots and potential roll-out barriers.

Results In a quantitative survey with $n = 543$ German respondents, we find that transport of CO_2 in comparison with capture, purification, and conversion of CO_2 into hydrocarbons is perceived as less acceptable, efficient, and useful, more expensive as well as damaging for the environment and health. Furthermore, product-step specific risk perceptions, as well as benefit and barrier perceptions for CCU mainly predict people's attitude towards the four production steps. A cluster-analysis revealed two groups, "Approvers" and "Sceptics", which were characterized by distinctive perception profiles. Further analysis showed that sustainability (e.g., use of renewable energy) and efficiency (e.g., carbon removal and resource use) were of greater importance to Approvers.

Conclusions The study's results suggest the need for further research and information provision to enhance public understanding of the technology and its role as a part of circular economy approaches. Risk perceptions play a central role in determining attitudes towards CCU, which should be considered in future studies and communication strategies. The findings can inform policymakers, industry stakeholders, and communication experts working to promote sustainable aviation fuel technologies.

Keywords Carbon capture and utilization, CO_2-based fuels, E-fuels, Public perception, Production step perception, Technology acceptance

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Background

As anthropogenic climate change continues to threaten increasing numbers of human lives and as estimations paint a picture of increasing and extreme climate change consequences, the need for greenhouse gas (GHG) abating measures and prompt action grows. The authors of the latest IPCC report assume that even for scenarios with very low GHG emissions the limit of 1.5 °C will "more likely than not" [1] be reached before 2040. Previous forecasts had to be discarded in favor of more critical assessments and it is expected that with reaching higher warming levels, the complexity and interaction of risks and climate change impacts will increase [1].

To achieve climate goals, both the reduction of future emissions and the removal of GHG by means of negative emission technologies is necessary [2]. The transport sector is highly dependent on fossil resources, cumulating to cause 37% of carbon dioxide (CO_2) emissions by end-use sectors in 2021 [3]. Carbon Capture and Utilization (CCU) is considered as a candidate for clean energy technologies that will be of use in the process of decarbonizing transport sectors, such as aviation and heavy transport [4]. CCU comprises the capture (e.g., from fossil or biogenic sources) and subsequent transformation of CO_2 into products, such as chemicals or building materials [5]. As one potential utilization pathway, CO_2-based fuels or e-fuels produced from CO_2, water, and renewable energy [6] offer the potential to reduce aviation sector emissions [7]. In 2021, the aviation sector accounted for around 720 Mt of global emissions [8] and it is estimated to grow (on average) by 3.3% per year until 2040 in terms of passenger numbers [9]. Therefore, a considerable proportion of emissions can be avoided in the future using e-fuels, which may become more appealing and economically feasible in the future, also due to more recent global crises and developments, such as the Ukraine war and rising fossil fuel prices. Accordingly, it is forecasted that the demand for e-fuels and e-chemicals could increase tenfold between 2030 and 2050 [10].

Perceptions of risks and benefits as well as acceptance by the public and other involved stakeholders can play a decisive role for the introduction and market success of new technologies or products. Although the CCU technology, its production steps, and infrastructure represent a set of large-scale technologies that is not directly used by end-consumers, their elements may still be visible and tangible to the public; they can support or reject them [11]; the latter can be reflected, for example, in opposition and protest, especially at the local level (e.g., [12]) as has been the case for the deployment of installations for power supply or wind energy [13], and carbon storage[14].

Therefore, the analysis of (risk) perceptions, perceived barriers, but also acceptance a) is crucial to identify potential roll-out barriers as early as possible and b) can offer insights to various stakeholders [15]. In the case of CO_2-based fuels, previous research has identified perception- and acceptance relevant impact factors for the fuel as an end-product, CCU as the underlying technological approach, as well as for involved infrastructure. To the best of our knowledge, however, the body of literature to date lacks detailed insights into the perception and acceptance of the process steps necessary to produce CO_2-based jet fuels. The perception of the CCU technology can impact the perception and acceptance of CO_2-based fuel as the manufactured end-product [16]. In view of this, this study analyzes whether there are acceptance hot spots among the necessary production steps and which (user) factors influence the public perception of the involved steps of the production of CO_2-based jet fuels.

Carbon capture and utilization/CO_2-based jet fuels

CCU is a technology that is set to reduce the environmental impact of emission-intensive (industrial) sectors. The growing global recognition of CCU is evident as numerous countries actively engage in advancing its technological development [17–19]. This study focuses on the production process for manufacturing CO_2-based fuels, which encompasses a series of essential steps, i.e., (a) the separation of CO_2 at a point-source [20], (b) the purification of the separated CO_2 (necessary for CO_2 streams with insufficient CO_2 stream purity) [21], (c) the transport of CO_2, and (d) the conversion of CO_2 into hydrocarbons [20].

CO_2 separation

CO_2 can be captured either pre- or post-conversion, i.e., CO_2 is separated before or after the carbon source has been converted into CO_2, or under the inclusion of O_2 for combustion (oxy-fuel combustion) [22]. Regardless of which of the three options is used, a considerable amount of input energy is needed for CO_2 capture [23]. Technologies used to separate CO_2 from flue gas streams are adsorption, (physical or chemical) absorption, and membrane-based separation. As different CO_2 sources come with differing combinations of flow rate, gas stream impurities or moisture levels in CO_2 streams, process configurations depend on the plant application while considering further conditions (e.g., costs). In planning of CCU supply chains, industrial plants are considered as supply sources due to their large flow rates of CO_2 [20].

CO_2 purification

CCU technologies often require a high purity and/or concentration of CO_2, which is why CO_2 purification is needed if gas stream purity and/or concentration is not high enough. This process step may be combined with CO_2 separation processes (e.g., using membrane-based separation) or added as a process step. Depending on the downstream requirements for further CO_2 utilization, it can be both cost- and energy intensive [24]. Impurities [e.g., nitrogen (N_2) and nitrogen oxides (NO_x)] need to be removed to avoid unintended reactions that can affect the process [21].

CO_2 transport

After separation (and if necessary, purification) of CO_2, it can be necessary to transport the CO_2 if it is not converted directly on-site. In this case, the CO_2 is transported to another production site for the next step, the conversion of CO_2 into carbon-based products. Transport is possible via pipeline, railway, and ship [25], as well as road transport (under specific distance and quantity circumstances) [10, 25]. Previous supply chain modelling has considered pipelines as the main (and economically most feasible) operation mode for transporting CO_2 [20, 26]. The properties of CO_2 require attention to certain points during transport planning: in comparison with other gases transported via pipeline, CO_2 leakages can pose greater risks, as transported liquid CO_2 will rapidly cool during expansion, potentially leading to impacts in the used pipeline infrastructure [27]. Additional factors that need to be taken into account for CO_2 transport decisions are, e.g., transport distance, pre-existing infrastructure, transport capacity, and properties of the CO_2 that is transported [10].

CO_2 conversion

Finally, CO_2 is converted into a carbon-based product, e.g., CO_2-based fuels. Currently investigated routes of fuel production include the production of methanol, dimethyl ether, or Fischer–Tropsch-fuels [28]. The conversion process considered for this study is the technological approach studied in the EU-funded eCOCO$_2$ project. Via electrocatalytic conversion, CO_2 is converted into chemical energy carriers (hydrocarbons) under the use of renewable electricity and water steam, to be used as synthetic fuel for aviation [29]. As the CO_2 conversion process is realized using renewable electricity, there is either the need for available renewable energy on-site, where CO_2 capture takes place, or CO_2 needs to be transported to places that offer an adequate supply of renewable energy [10].

CO_2-based jet fuel usage

This study focuses on the production steps used to manufacture CO_2-based fuels for the aviation sector using the CCU approach. CCU technology development has increased over the last decades. However, there are hurdles yet to be overcome and many CCU technologies are currently still in lower levels of technology maturity [30], depending e.g., on the production step. In 2023, post-combustion capture of CO_2 in case of the cement or steel industry has reached a technology readiness level (TRL) of 6 [31], while approaches such as conversion via electrochemical membrane reactors (similar to the process in the considered eCOCO$_2$ project) are at TRL 3–4 [32]. For e-fuels, TRL ranges from 5 to 6 (high temperature Fischer–Tropsch) to 8 (methanol) [33]. Significant emission reduction potentials are attributed to CCU. Nevertheless, these assessments are based on scenarios that require for example significant financial expenditure (e.g., due to the need to build new plants) by those industries that in the future would use CO_2 as feedstock, i.e., changes that can be labeled as 'a highly disruptive course of action' [30]. CO_2-based fuels in particular are currently not economically attractive without subsidies, such as carbon credits [34]. From a regulatory perspective, the Renewable Energy Directive II recognized CO_2-based or e-fuel in 2018. However, until 2023, only a small number of countries have legal frameworks that could foster the implementation of these fuel alternatives. To allow them to compete with conventional fuels, regulatory intervention is needed [35]. Policy efforts such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) intend to keep CO_2 emissions at 2020 levels by compelling airlines to offset any increase beyond 2020 levels [36]. However, it is important to note that these measures can have unintended consequences, such as carbon leakage through the use of alternative flight routes or distortion of competition [37].

Regarding technology development, estimates for cost scenarios for the operation of CCU at an industrial scale need to be developed for the near to distant future to check for aspects such as energy efficiency or current density at a bigger scale [38]. In addition to economic and technological obstacles, there is the requirement for a more in-depth comprehension of the environmental advantages associated with utilizing CO_2 in diverse applications throughout life-cycle analysis [30].

Despite technical, economic, and regulatory challenges to be overcome, CCU offers several benefits, including pathways towards a circular economy [39] by utilizing CO_2 and converting it into higher value materials, such as polyols [40] or concrete [41]. From an industrial point of view, there are currently limited short-term options for large-scale CO_2 reduction besides carbon capture for heavy industries, such as steel and cement [42].

Furthermore, complementary to hydrogen-based solutions, CCU can address the demand for sustainable fuels in heavy-transport sectors, such as maritime [43] and aviation [44]. The production of CO_2-based fuels (and other e-chemicals), however, depends on a large amount of electricity, which would preferably be generated from renewable sources. Accordingly, this production path competes with other applications of renewable energy, such as electricity supply and heat generation [45].

Although CO_2-based jet fuel may have a lower impact on the environment in terms of greenhouse gases, the combustion of alternative aviation fuels does not eliminate the influence of other climate-impacting factors, such as contrail heating, which also occurs when CO_2-based fuel is burned [46]. However, according to Ballal et al. [47], the combustion of alternative aircraft fuels results in lower soot emissions, leading to less ice crystal formation in contrails and, consequently, a reduced global warming effect [47]. Considering the aspect of carbon neutrality, options such as CO_2-based fuel production based on bioenergy (under certain conditions) [48], or Direct Air Capture (DAC) can be considered carbon neutral [10]. However, there are industries such as the cement industry that are facing the problem of currently unavoidable emissions. Utilizing emissions from these point sources offers the opportunity to produce fuels with a smaller impact than fossil-based, conventionally used fuels—as the carbon is reused instead of being extracted from fossil reserves—for a transport sector, such as aviation [10], which is estimated to grow [9] and is far from being able to utilize technologies such as electrification for commercial air traffic [8, 49].

Technology (risk) perception and acceptance of CCU technologies and infrastructure

Technology acceptance

Apart from potential benefits in CO_2 emissions reduction, CCU—as any technological innovation—is linked to two crucial factors that social science research increasingly focuses on: public perception in terms of perceived barriers and benefits, and acceptance. Among other crucial aspects, such as technical, economic or governance feasibility [50] or environmental impacts on e.g., the atmosphere and biodiversity [51], these factors play a significant role in the successful implementation of new technologies or consumer goods, such as CO_2-based fuels. Lack of public acceptance has the potential to hinder the adoption of innovative technologies, due to protests or reluctance towards climate-friendly innovations [52, 53]. However, it is not only the lack of acceptance for marketable end-products in the roll-out process which is decisive. Typically, there is also a lack of knowledge of acceptance of production process criteria, i.e., which acceptance-related factors should have been recognized during the technology development [16, 54]. Therefore, it is essential to assess technology perceptions and acceptance by all stakeholders, including the public, as early as possible, i.e., also during the developmental phase of a technology and its infrastructural elements [54–56]. Regularly and empirically examining and addressing perceptions of technology is a crucial cornerstone in informing technology development and shaping effective communication activities. By actively identifying and addressing any (mis)conceptions associated with the technology, stakeholders can make informed acceptance decisions grounded in verifiable information.

Technology acceptance is defined as the active or passive approval of a technology or product, encompassing its development, implementation, and usage [57]. It describes a dynamic process whereby participating stakeholders, including the general public, constantly re-evaluate their attitudes towards the technology [58]. *Public perception* refers to the cognitive and affective evaluations that individuals associate with a technology, encompassing perceived benefits, barriers, and risks [59]. Public perceptions and technology acceptance are closely intertwined, as the former significantly influences the latter. As demonstrated by Huijts et al. [60], perceived benefits and risks have a significant impact on an individual's attitudes, which in turn influences their intention to accept or adopt a technology [60].

In the context of sustainable energy, Wüstenhagen et al. [61] have conceptualized three dimensions of acceptance, while also identifying (a) the actors involved and (b) the factors influencing acceptance decisions within each of these realms. *Socio-political acceptance* refers to the general acceptance of a technology on a broader level by stakeholders, such as the public, policy makers, and other relevant actors. *Community acceptance* addresses the approval of local energy projects, emphasizing factors such as trust or procedural justice. *Market acceptance*, on the other hand, pertains to the adoption of a technology on a large-scale through consumer or investor adoption [61]. While all three dimensions are critical for the successful implementation of a technology, this study specifically examines the socio-political acceptance of the production steps involved in manufacturing CO_2-based fuels.

Acceptance and perception of CCU and CCU products

Although many CCU projects are still in the pilot phase, there is a growing body of research investigating public perception as well as (laypeople's) acceptance of the technological approach of CCU, production steps involved, and CCU-derived products.

Degrees of general technology acceptance of CCU range between moderate (with average responses deviating only marginally from the mid-point of the scale towards a positive assessment) [59] and rather high [62]. At the same time, laypeople's awareness and knowledge of the technology is rather low [11, 62, 63]. Despite the low level of knowledge, the moderate to positive acceptance ratings indicate a general openness towards the concept of CCU.

Regarding the influence of technology perception on acceptance of CCU, *benefit perceptions* (e.g., perceived environmental, policy benefits) are a strong positive impact factor for acceptance, i.e., the more the technological approach of CCU is perceived as beneficial, the more it is accepted [16, 64]. Perceived benefits identified during an interview study with CCUS related stakeholders identified both global but also local benefits (e.g., in terms of labor and industry opportunities) for the region that will potentially be the location of CCUS projects [65]. Conversely, *barrier perceptions* negatively impact acceptance, e.g., perceived policy and sustainability barriers [16], as well as perceptions of delays in emission reduction and investments in sustainable technologies [62] or the perception that implementing CCU is to be interpreted as tampering with nature [63]. Similarly, risk perceptions are accompanied by a negative influence on CCU acceptance [63, 64]. A study by Arning et al. [62] observed that CCU related risks are predominantly not connected to human health or the environment in general, but to the risk of CO_2 leakage during production [62]. In a study comparing the influence of CO_2 source, CO_2-derived product, and profitability of a CCU site on acceptance, profitability was found to be the most decisive. It turned out that for laypeople it mattered the most that no public financing is involved (vs. long-term and start-up public financing), compared to various options of CO_2 sources and manufactured products [54]. Results on impacts by user-related factors on acceptance are mixed, as for example one study found no impact by user factors, such as age, education or gender [62], while another study reported that gender and technical self-efficacy showed to have an influence [11]. Conducting a thorough analysis that specifically examines the individual steps involved in the production of CO_2-based jet fuels through CCU could offer insights into the influence of personal variables on risk perceptions and technology acceptance. This analysis would not only consider the final product itself but also explore how personal variables might impact the perception of the production process itself.

Parallel to CCU as a technological approach, CO_2-derived products have been the object of perception and acceptance studies. Results indicate rather high levels of acceptance and willingness to use CO_2-derived products, such as carbonated beverages [66], insulation boards [67], and CO_2-based fuels [16], which were found to be preferred as a potential product in a study by Offermann-van Heek et al. [68]. In comparison with conventional fuels, CO_2-based fuels were assessed to be safer, more eco-friendly, less toxic, cleaner, and less harmful [69].

For the specific case of CO_2-based jet fuel, perceived benefits were (again) identified as a predictor of acceptance [16] and willingness to use [66]. For CO_2-based jet fuel, perceptions of advantages include environmental benefits but also the perceived potentials for the specific case of aviation, as it is perceived as a much-needed measure in this sector and ensures flying as a mode of transport [16]. Again, risk perceptions can impact acceptance [66, 70], although in case of CO_2-based fuel it was found that there is no elevated risk assessment by laypeople for various risk targets (e.g., one's own health, flora and fauna) [69]. For user factors, several sociodemographic (e.g., education, nationality [71]) and attitudinal factors (e.g., environmental awareness [66] and flight shame [71]) were observed to influence the acceptance of CO_2-based products. Other factors, such as the knowledge about carbon dioxide, did not seem to have an influence [66]. Conversely, a study by Dowd et al. (2014) linked low levels of knowledge about CO_2 to misconceptions and perception of CCS [72]. For an in-depth analysis of the perception of CCU production steps, the factor of CO_2 knowledge may still be of relevance and should not be omitted from consideration.

Perception of CCU production steps

The analysis of positive or negative attitudes towards production steps and the ability to identify predictors of these attitudes are central aspects of studying the relationship between production perception and acceptance in the context of CCU. To the best of our knowledge, this has not been undertaken yet. Nevertheless, individual production steps have been studied before, for example in the context of CCS. Although CO_2 is not stored underground in the specific case of CCU, it still needs to be separated and likely transported first. However, it can be assumed that the overall assessment of CCS could influence the perceptions of the individual steps. Then again, it gives a first insight into the perception of each step, an insight that is still partly missing from the perspective of CCU and whose gap the present study aims to close.

For the first production step, *CO_2 capture*, Arning et al. (2018) determined that the perception of a CO_2 source can vary between scenarios, as steel plants were assessed positively, while coal-fired plants were not preferred as places for CO_2 capturing (likely due to the option of renewable energy sources) [54]. Wallquist et al. (2012) observed that a fossil gas plant was rejected, while biogas-fired plants were preferred for CO_2 capture [73]. Interestingly, there are inconclusive results between studies touching on proximity to a capture site. While some findings conclude a positive connection between proximity to and support of CO_2 capture [74], others prefer capturing to take place in neighboring areas instead of their own [73]. As for international management of CO_2, Merk et al. [75] hypothesize that cross-border transport of CO_2 was rejected by Norwegians in their study because of the belief that domestic emissions are the emitting country's responsibility, and that capture (and storage) should therefore take place domestically [75].

As for *transport of CO_2*, a qualitative study found that six out of ten interviewed people from an area where a CCS project was supposed to be implemented felt that transport of CO_2 via pipeline was going to be "quite" to "very unsafe" [14]. Notably, risk perceptions surrounding CO_2 transport are a recurrent theme in public perceptions, as another study observed that ensuring the safety of onshore CO_2 transport was a topic of elevated relevance to participants from the UK and the Netherlands. Nearly half of voiced arguments for negative assessment (NL: 44.5%, UK: 45.9%) were referring to safety, risk or monitoring concerns, with leakage and resulting harm playing a prominent role in argumentation [76].

For *purification and conversion of CO_2*, we did not come across previous empirical results on public perception. A potential reason for this could be that the relatively new body of research in the field of CCU until now focused on technological development, its economic viability, and environmental impacts. Further research on the topic of production step perception is therefore needed.

Methods

Research questions and empirical approach

Previous research investigated both public perception and acceptance of the CCU technology as well as potential CCU products, such as CO_2-based fuel. It has been previously established that there is a connection between how laypeople perceive a technological approach and their acceptance of a product resulting therefrom [16]. Previous studies have not thoroughly investigated the perception of the individual CCU production steps in the context of aviation fuel production. Here it is important to bear in mind that an empirical examination of perceptions and acceptance of these production steps from the perspective of laypersons is not intended to lead to the abolition of (technically) necessary production steps. Rather, we aim to identify sources of misconceptions, to identify potential "hotspots" for risk perceptions, and to identify information needs and communication requirements.

Based on the previous literature review and the identified research gap, the following study aims and research questions were formulated.

Aim 1: Assess and contrast perceptions and evaluations of CCU process steps.

RQ 1: Are there differences in laypeople's perceptions and attitudes between the CCU production steps?

Aim 2: Identify impact factors for the evaluation of CCU production steps.

RQ 2: Which (user) factors affect laypeople's attitude towards the CCU production steps?

RQ 2.1: Which (user) factors affect laypeople's attitude towards CO_2 separation?

RQ 2.2: Which (user) factors affect laypeople's attitude towards CO_2 purification?

RQ 2.3: Which (user) factors affect laypeople's attitude towards CO_2 transport?

RQ 2.4: Which (user) factors affect laypeople's attitude towards CO_2 conversion?

Aim 3: Provide an in-depth understanding of lay perceptions for production-related processes.

RQ 3: Which further requirements are formulated for the individual CCU production steps?

Measurement instrument

At the beginning of the survey, respondents were informed about the purpose and data privacy of the study. After stating their informed consent, they provided information on demographic and attitudinal user factors (see Fig. 1). Next, participants were instructed to read a short informational text on the production of CO_2-based

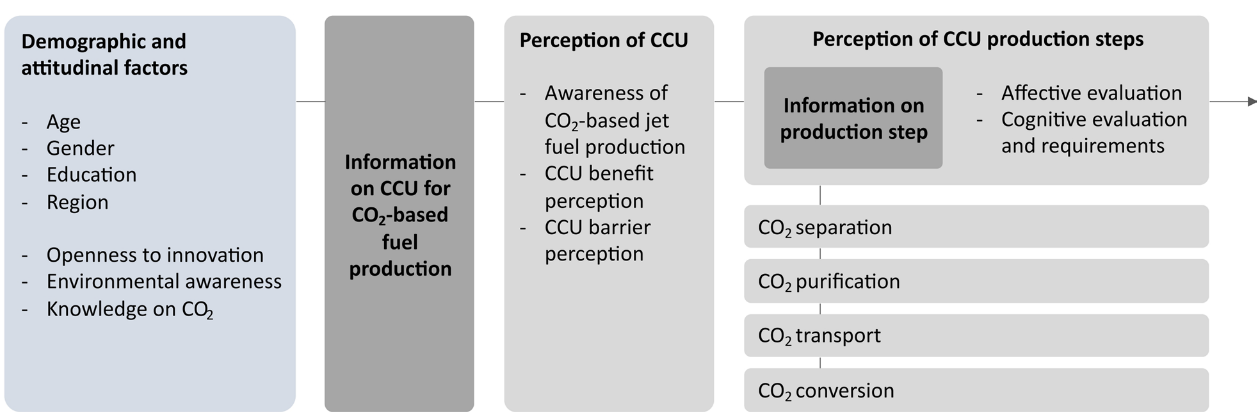

Fig. 1 Structure of and assessed constructs in the survey

jet fuel based on the CCU approach. The information text (see Additional file 1 for instructional material) was developed together with the technical experts from the eCOCO$_2$ project consortium and checked for factual correctness and comprehensibility in pretests.

In the following, participants answered questions concerning their awareness of CO_2-based fuel production and their benefit and barrier perceptions towards CCU. After that, the perception of production steps was assessed following a recurring pattern: first, a short explanation of the respective production step was presented. Next, respondents indicated their affective evaluation of that production step as well as their (dis)agreement to individual items that, for example, formulated conditions of production for the respective step, which were determined in exchange with technical experts from the eCOCO$_2$ project. A six-step semantic differential [77] was employed as the assessment tool to evaluate the perceptions of the CCU production steps. Participants were asked to provide their evaluations based on the dimensions presented in the differential scale. This was done separately for the steps of CO_2 separation, CO_2 purification, CO_2 transport, and CO_2 conversion into hydrocarbons.

Respondents' answers were collected using 6-point Likert scales ranging from 0 = *strong disagreement* to 5 = *strong agreement*. The mid-point of the scales was 2.5; accordingly, mean values below 2.5 were judged as disapproving judgments and mean values above 2.5 were judged as approving judgments. In case of CO_2 knowledge, respondents had the opportunity to indicate their lack of knowledge by choosing 'I don't know' in addition to the 6-point Likert scale. Item battery-internal randomization was used to prevent sequence effect bias. A complete list of the used items and constructs, including references, can be found in Additional file 1: Table S1. Before data collection, the survey structure, contents, and data management were checked by the Ethics Committee of the Faculty of Arts and Humanities at RWTH Aachen University and were approved for empirical use.

Data collection and preparation

Data collection took place in the fall of 2020 and was conducted through a market research company. To acquire a representative sample, we used quotas tailored to the German population for age groups per gender, education levels (low, medium, and high; based on the International Standard Level of Education, ISCED) [78], and regions. Respondents were excluded from participation if the set quotas were full. For sufficient data quality, individuals were also excluded in case of failed quality checks, survey termination, speeding (i.e., a response time < 35% of the median), and internal inconsistency (i.e., equal response behavior for contradictory item contents). The final sample consisted of $n = 543$ data sets from German participants. On average, it took participants 23.0 min ($SD = 10.16$ min) to complete the survey.

After collection, data for singular items were inverted, so that low values refer to disagreement and high values to agreement.

Statistical analyses

Prior to inference statistical analysis, item analyses were conducted to ensure measurement quality. Cronbach's alpha was calculated to test for internal construct consistency (see Table 1 for construct formation). Principal

Table 1 Cronbach's alpha and descriptive statistics for computed constructs

Construct	Number of items	Cronbach's α	M	SD
Environmental awareness	5	0.676	3.42	0.90
CO_2 effect knowledge	3	0.551	3.84	0.78
CO_2 chemical knowledge	2	0.640	2.93	1.23
Openness to innovation	3	0.566	2.34	0.87
Awareness of CO_2-based jet fuel production	2	0.630	0.91	1.02
Attitude towards CO_2 separation	6	0.899	3.07	1.10
Attitude towards CO_2 purification	6	0.884	3.13	0.95
Attitude towards CO_2 transport	6	0.906	2.53	1.05
Attitude towards CO_2 conversion	6	0.902	3.07	0.99
CCU benefit perception	9	0.916	3.09	0.84
CCU barrier perception	7	0.817	2.68	0.78
Risk perception for separation of CO_2	2	0.732	2.03	0.99
Risk perception for purification of CO_2	1	–	1.70	1.05
Risk perception for transport of CO_2	4	0.787	2.58	0.91
Risk perception for conversion of CO_2	3	0	2.34	0.90

component analyses (PCA) were utilized to identify underlying factors in the data. Distributional assumptions were tested prior to performing parametric testing procedures. If these were not met, nonparametric procedures were used. Bi-variate correlations were conducted to analyze the relationships between user factors. Furthermore, we used analyses of variance (ANOVA) with repeated measures, to identify differences for answers given at different points during the survey. Step-wise multiple linear regression was applied to exploratorily check which factors predict the attitude towards the production steps. The sample was screened for underlying groups with similar answering patterns using a two-step cluster analysis (hierarchical and k-means cluster analysis). Finally, one and two-sample *t* tests were used to identify differences between groups and to check for deviance from the mid-point of scales, i.e., for tendencies in answering behavior. The level of significance was set at 5%.

Construct formation

To check for underlying structures in the survey items, the items were included in factor analyses. We included all *knowledge*-related items from the survey in a PCA, i.e., items whose content formulated an assumption about, e.g., climate change, CO_2, or sustainable technologies. Bartlett's Test of Sphericity was significant ($p<0.001$) and the Kaiser–Meyer–Olkin (KMO) measure was 0.684, indicating appropriate levels of sampling adequacy. The PCA results justified the extraction of four factors with eigenvalues above 1 (see Table 1 for all constructs): *Environmental awareness* ($\alpha=0.68$, five items), e.g., "I think that CO_2-emissions have a strong influence on climate change.", *CO_2 effect knowledge* ($\alpha=0.55$, three items), e.g., "CO_2 is toxic to humans in high concentrations.", *CO_2 chemical knowledge* ($\alpha=0.62$, two items), e.g., "Naturally and industrially produced CO_2 are chemically different in composition.", and *Awareness of CO_2-based jet fuel production* ($\alpha=0.63$, two items), e.g., "I have a very good knowledge of the topic the production of CO_2-based fuels."

In addition, two constructs were built, respectively, relating to perceived benefits and barriers of CCU: *CCU benefit perception* ($\alpha=0.92$, nine items), e.g., "CCU contributes to saving fossil resources." and *CCU barrier perception* ($\alpha=0.82$, seven items), e.g., "CCU will become an excuse for factories to keep on emitting CO_2."

Another construct that was calculated relates to *Openness to innovation* ($\alpha=0.57$, three items), e.g., "I am often one of the first in my circle who accepts an innovation." Finally, for every production step included in the study, a construct for *Attitude towards [production step]* was formed. Although fitting to the definition of acceptance as an active or passive approval of a technology or product, encompassing its development, implementation, and usage [57], we are not referring to the production step evaluation as acceptance of [production step] in this study. Based on the items used to form the constructs, we find the use of the wording *Attitude* more fitting for the dynamic, reiterative process of re-evaluation of attitudes [58]. Constructs were, respectively, formed based on the six semantic differential items that were surveyed for each production step and the end-product CO_2-based jet fuel: "unacceptable–acceptable", "not useful–useful", "damaging for the environment–environmentally friendly", "inefficient–efficient", "expensive–cheap", and "health damaging–not health damaging".

Sample

In total, 543 German participants took part in the survey. Of this sample, 50% each were female ($n=271$) or male ($n=272$) with a mean age of 45.0 years ($SD=15.2$, 18–70 years). The share of individuals with low education levels was 15.8%, followed by the highly educated group with 28.7%. Most of the participants indicated that they had achieved a qualification of medium education level (55.4%). On average, the sample was rather environmentally aware ($M=3.42$, $SD=0.9$) and participants' knowledge of the effects of CO_2 (e.g., on the climate) was rather high ($M=3.84$, $SD=0.78$). Their knowledge on chemical characteristics of CO_2 (e.g., that naturally and industrially produced CO_2 are chemically the same in composition) was not as high ($M=2.93$, $SD=1.23$), yet still significantly differing from the mid-point of the scale of 2.5 ($t_{490}=7.85$, $p<0.001$, $d=0.354$). Overall, openness towards innovation ($M=2.34$, $SD=0.87$) was rather low ($t_{542}=-4.28$, $p<0.001$, $d=-0.184$).

Age was negatively associated with environmental awareness ($r=-0.097$, $p=0.025$, see Table 2), openness to innovation ($r=-0.201$, $p<0.001$), and participants' knowledge of effects of CO_2 ($r=-0.094$, $p=0.028$). With increasing age, scores for the three attitudinal factors decrease. Regarding gender, women reported higher levels of environmental awareness ($r=-0.109$, $p=0.011$), while men indicated a higher openness to innovation ($r=0.116$, $p=0.007$) and knowledge on CO_2's chemical characteristics ($r=0.270$, $p<0.001$). Higher levels of education also correlated positively with openness to innovation ($\tau b=0.083$, $p=0.019$), as well as knowledge about CO_2 effects ($\tau b=0.161$, $p<0.001$) and chemical characteristics ($\tau b=0.141$, $p<0.001$). Participants with higher levels of CO_2 effect knowledge also were more environmentally aware ($r=0.362$, $p<0.001$) and more open to innovation ($r=0.153$, $p<0.001$).

Table 2 Pearson and Kendall's tau correlations for demographic and attitudinal characteristics

	1	2	3.[b]	4	5	6
1. Age	–					
2. Gender[a]	0.009	–				
3. Education[b]	−0.034	0.093*	–			
4. Environmental awareness	−0.097*	−0.109*	0.054	–		
5. Openness to innovation	−0.201***	0.116**	0.083*	0.022	–	
6. CO_2 effect knowledge	−0.094*	0.048	0.161***	0.362***	0.153***	–
7. CO_2 chemical knowledge	0.025	0.270**	0.141***	−0.051	0.067	0.028

*p < .05, **p < .01, ***p < .001; [a]gender dummy-coded: 0 = female, 1 = male; [b]Kendall's tau correlation

Results

Evaluation of production steps (RQ 1)

To compare the evaluation of CCU production steps, we analyzed the data to detect any variations in respondents' responses regarding the dimensions used to assess these steps.

An ANOVA with repeated measures revealed that there is a significant difference in people's mean evaluation of the steps for the semantic differential "unacceptable–acceptable" [$F(2.55, 1384.03) = 70.37$, $p < 0.001$, partial $\eta^2 = 0.12$] (see Fig. 2). A Bonferroni post-hoc test revealed that there are significant differences between transport of CO_2 and all other production steps, as it is perceived to be less acceptable (see Additional file 1: Tables S2–S7 for pairwise comparisons and descriptives). The transport step still was perceived to be rather acceptable than unacceptable, as the mean value for this item ($M = 2.94$, $SD = 1.31$) is significantly different from the mid-point of the scale (2.5) ($t_{542} = 7.89$, $p < 0.001$, $d = 0.34$).

A similar picture emerged for "not useful–useful" [$F(2.55, 1379.97) = 115.77$, $p < 0.001$, partial $\eta^2 = 0.18$], as post-hoc Bonferroni tests show that transport of CO_2 again is significantly less perceived to be useful ($M = 2.75$, $SD = 1.36$) than all other production steps. Nevertheless, perception still leans more towards usefulness ($t_{542} = 4.33$, $p < 0.001$, $d = 0.19$). In addition, separation of CO_2 ($M = 3.47$, $SD = 1.42$) is significantly less perceived as useful than the step of purification ($M = 3.67$, $SD = 1.2$, $p < 0.001$).

For "damaging for the environment—environmentally friendly", we again found a significant difference between transport of CO_2 and the remainder of production steps [$F(2.62, 1419.77) = 95.68$, $p < 0.001$, partial $\eta^2 = 0.15$]. In this case, however, transport of CO_2 is perceived as rather damaging for the environment ($M = 2.36$, $SD = 1.25$,

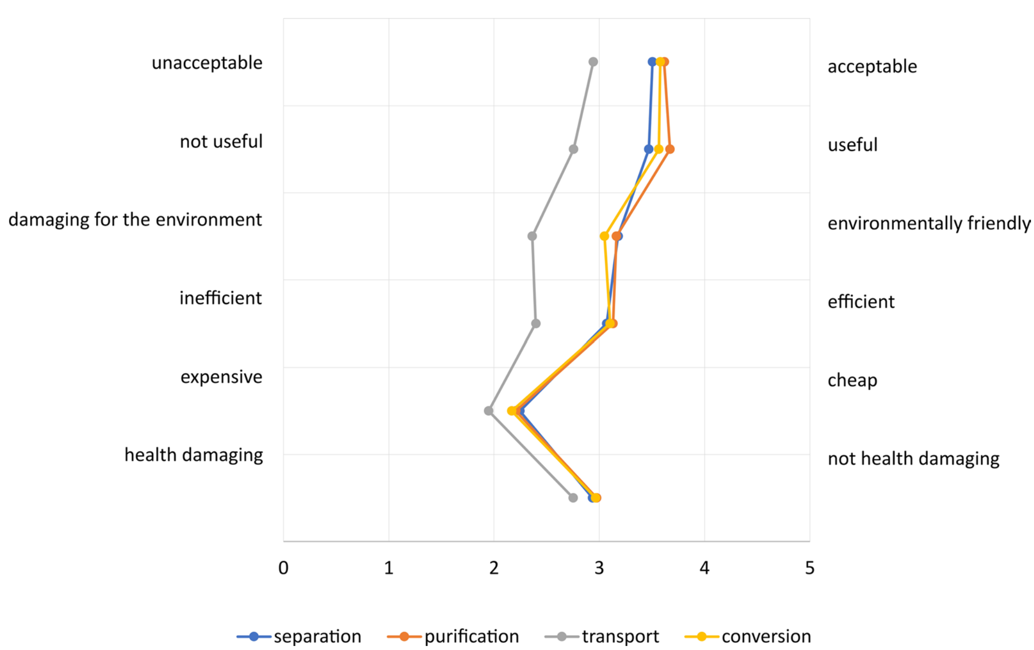

Fig. 2 Mean agreement for semantic differential evaluations of the production steps

$t_{542}=-2.6$, $p=0.01$, $d=-0.11$), while the other steps are perceived as environmentally friendly (e.g., conversion of CO_2: $M=3.05$, $SD=1.23$, $t_{542}=10.43$, $p<0.001$, $d=0.45$).

For the pairing "inefficient—efficient", the mean perception of transport of CO_2 (M = 2.4, $SD=1.28$) does not significantly differ from the mid-point of the scale (2.5) ($t_{542}=-1.89$, n.s.), so no positive or negative trend can be discerned across the sample. Separation, purification, and conversion of CO_2 are significantly more perceived to be efficient [$F(2.68, 1454.42)=90.87$, $p<0.001$, partial $\eta^2=0.14$].

While transport of CO_2 is significantly more perceived to be expensive than the remainder of production steps [$F(2.79, 1511.88)=14.63$, $p<0.001$, partial $\eta^2=0.03$], these are also perceived to be expensive instead of cheap (e.g., separation of CO_2: $M=2.24$, $SD=1.25$, $t_{542}=5.15$, $p<0.001$, $d=0.22$).

Finally, for "health damaging—not health damaging", an ANOVA with repeated measures showed that there are significant differences [$F(2.83, 1030.13)=9.27$, $p<0.001$, partial $\eta^2=0.02$]. Bonferroni post-hoc analysis revealed that it is again the transport of CO_2 that significantly differs from the rest of production steps. Despite this difference, transport of CO_2 overall still is perceived to be rather not health damaging ($M=2.75$, $SD=1.21$, $t_{542}=4.82$, $p<0.001$, $d=0.21$).

Attitude towards CO_2-based fuel production steps (RQ 2)

The second aim of this study was to identify impact factors on the evaluation of CCU production steps. Prior to carrying out step-wise multiple linear regressions to predict the attitude towards the single production steps, assumptions of multiple linear regression were checked [79]. P–P plots of the regression standardized residuals and histograms of residuals were checked for (near) normality of data. The inspection of scatterplots revealed that homoscedasticity assumptions were fulfilled. Multicollinearity diagnosis showed that predictors show some relationship but do not correlate too strongly (i.e., > $r=0.7$). In addition, to check for multicollinearity, tolerance (> 0.1) and variance inflation factors (VIF) values (< 10) were consulted. Durbin–Watson statistics were assessed to make sure there is no autocorrelation of residuals. Cook's distance (< 1) was utilized for each data set to check for outliers. Adjusted R^2 was used to assess model fit (see Additional file 1: Tables S8–S12 for regression results).

Prediction of the attitude towards CO_2 separation

Based on the predictors included in a step-wise linear regression, 46.0% of variance were explained for the attitude towards the first production step, *separation of* CO_2 [$F(5, 485)=84.54$, $p<0.001$]. Figure 3 depicts the

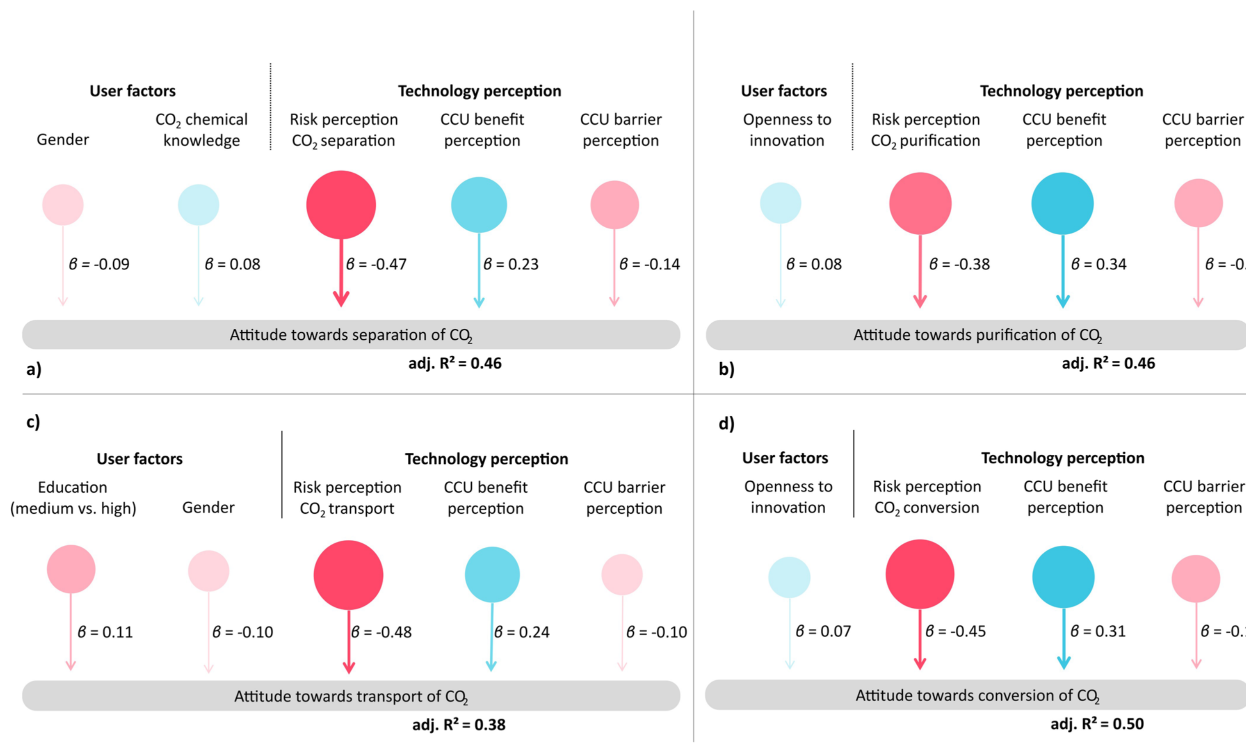

Fig. 3 Results of step-wise multiple linear regressions for *attitudes towards* **a** *separation*, **b** *purification*, **c** *transport*, **d** *conversion of* CO_2; size of circles and shade of color indicate the size of standardized beta coefficients (β), blue = positive influence, red = negative influence of predictors

regression analysis results for the step of CO_2 separation as well as the subsequent process steps.

Based on the standardized coefficients, respondents' *risk perception* best explains the attitude towards this first production step ($\beta=-0.47$, $p<0.001$). This is followed by benefit ($\beta=0.23$, $p<0.001$) and barrier perceptions ($\beta=-0.14$, $p<0.001$) of the CCU technology. The two user factors explaining attitude towards separation of CO_2—although to a small degree based on the standardized beta coefficients—are chemical CO_2 knowledge ($\beta=0.08$, $p=0.035$) and gender ($\beta=-0.09$, $p=0.011$). Respondents with a higher knowledge of the chemical characteristics of CO_2 have a more positive attitude. There were also differences between the perceptions of women and men: women reported a more positive attitude than men. The variables age, awareness of CO_2-based jet fuel production, CO_2 effect knowledge, education, environmental awareness, and openness to innovation were not included as predictors in the regression model.

Prediction of the attitude towards CO_2 purification

The step-wise multiple linear regression for the prediction of CO_2 purification attitude explained an adj. R^2 of 46.2% [$F(4, 486)=106.32$, $p<0.001$].

The analysis of standardized beta coefficients shows that again the risk perception in connection with the specific step of CO_2 purification is the largest predictor for this production step ($\beta=-0.38$, $p<0.001$). CCU benefit perception is a nearly as strong—although positive—predictor ($\beta=0.34$, $p<0.001$), followed by negatively influencing CCU barrier perception ($\beta=-0.16$, $p<0.001$). Using regression analysis, only one user factor was identified as an attitude predicting factor: the more open people are towards innovation in general, the more positive their attitude towards the purification of separated CO_2 ($\beta=0.08$, $p=0.022$) (excluded variables: age, awareness of CO_2-based jet fuel production, CO_2 chemical knowledge, CO_2 effect knowledge, education, environmental awareness, and gender).

Prediction of the attitude towards CO_2 transport

For the third production step, the transport of separated and (if needed) purified CO_2, we found that the included variables could explain 38.4% of variance [$F(5, 485)=62.13$, $p<0.001$].

The analysis of standardized beta coefficients allowed us to identify the variables that significantly predict the evaluation of CO_2 transport: as was the case for separation and purification of CO_2, risk perception regarding the transport of CO_2 is the most prominent negatively attitude-related factor ($\beta=-0.48$, $p<0.001$). CCU benefit perception predicts the attitude towards CO_2 transport with half of that predictive power ($\beta=0.24$, $p<0.001$). This is followed by the negatively impacting predictor CCU barrier perception ($\beta=-0.10$, $p=0.012$). Regarding user factors, people with a medium level education have a more positive attitude than higher educated respondents ($\beta=-0.11$, $p=0.002$), as do female in comparison with male respondents ($\beta=-0.10$, $p=0.011$) (excluded variables: age, awareness of CO_2-based jet fuel production, CO_2 chemical knowledge, CO_2 effect knowledge, environmental awareness, and openness to innovation).

Prediction of the attitude towards CO_2 conversion

Based on the predictors included in a step-wise linear regression, 49.9% of variance could be explained for the attitude towards the final production step, the conversion of CO_2 into hydrocarbons [$F(4, 486)=123.03$, $p<0.001$].

Based on the standardized coefficients, four predictors were identified: as was the case in the previous analyses, risk perception is the factor with the most predictive power in the analysis ($\beta=-0.45$, $p<0.001$). The more a person perceives the conversion of CO_2 into hydrocarbons to pose risks, the more negative their attitude towards this production step. The same applies to CCU barrier perceptions, which add a smaller impact factor to the picture ($\beta=-0.11$, $p=0.002$): the more respondents evaluate CCU as a technological approach to be connected to barriers, the less positive their attitude of CO_2 conversion (and vice versa). CCU benefit perception has the opposite impact, as an increase in benefit perception results in an increase on positive attitude ($\beta=0.31$, $p<0.001$). The same applies to openness to innovation ($\beta=0.07$, $p=0.047$), the only user factor in the regression model of the final production step (excluded variables: age, awareness of CO_2-based jet fuel production, CO_2 chemical knowledge, CO_2 effect knowledge, education, environmental awareness, and gender).

Evaluation of production step requirements (RQ 3)

The analysis of regression models for production step assessment determined risk perceptions as a central predictor of attitude towards the production steps. In addition to the assessment of risk perceptions, participants indicated their agreement to several statements for each production step that allow for a deeper analysis of laypeople's evaluation of the required steps of CO_2-based fuel production [16, 80]. For this reason, we believe it makes sense to additionally focus on the conditions and (differences in) risk perceptions associated with the production steps that go beyond the general attitude towards a production step. By doing so, the analysis of a rather affective attitudinal evaluation is complemented by cognitive assessment of specific production conditions [64].

Identifying perception profiles

To provide an in-depth understanding of lay perceptions for production-related processes we used a two-step cluster analysis (hierarchical and k-means cluster approach) to identify groups of people with specific attitudinal profiles. Therefore, we included the five constructs measuring participants' attitudes towards the production steps and the end-product and included them in a hierarchical cluster analysis (Ward method). The results indicated a two-cluster solution to be the best fit. A subsequent k-means cluster analysis with two clusters grouped the sample into two distinct clusters. ANOVAs affirmed the cluster fit, as the two identified clusters significantly differed in user characteristics (see Table 3), most of which also were identified as crucial factors in the preceding regression analyses.

Participants grouped in Cluster 1 were significantly younger, less environmentally aware, and less open to innovation, while they had a significantly lower degree of knowledge when it comes to chemical characteristics of CO_2. Regarding perception of and attitude towards the studied production steps and the CCU technology in general, we find that Cluster 2 participants have a significantly more positive attitude towards all production steps, while also perceiving the CCU technology to be beneficial or to be posing less barriers than is the case for Cluster 1. Therefore, we coined Cluster 1 as *Sceptics*, as their mean agreement is often slightly above or below the center of the scale (2.5). According to participants' average ratings in Cluster 2, this group is named *Approvers*.

Perception of material and energy utilization

During the survey, participants were instructed to assess several items that formulate conditions of production. A factor analysis revealed two underlying factors in this group of items: according to their semantic content they can be titled as *Perception of material and energy utilization* and *Perception of plant conditions*. The first group of items groups together statements regarding requirements and perception towards material utilization, e.g., "The separation of CO_2 is only useful, if it is done using renewable energy" Fig. 4 depicts the average ratings for the whole studied sample, as well as for the identified groups of *Sceptics* and *Approvers*. One aspect that was analyzed for the production steps separation, purification, and conversion of CO_2 is the use of renewable energy. For all three of these, there are significant differences between the two groups. Approvers agreed significantly more than the group of Sceptics to the statement that separation ($M_{Appr} = 3.59$, $SD = 1.17$, $M_{Scept} = 3.31$, $SD = 1.1$), purification ($M_{Appr} = 3.67$, $SD = 1.09$, $M_{Scept} = 3.32$, $SD = 1.06$), and conversion of CO_2 ($M_{Appr} = 3.76$, $SD = 1.07$, $M_{Scept} = 3.48$, $SD = 1.08$) is only useful, if the respective step is done via use of renewable energy [$t_{sep}(541) = -2.89$, $p = 0.004$, $d = -0.25$; $t_{pur}(541) = -3.81$, $p < 0.001$, $d = -0.33$; $t_{conv}(541) = -3.0$, $p = 0.003$, $d = -0.26$]. Interestingly, for the overall sample, the use of renewable energy is a more important requirement in case of conversion of CO_2 ($M = 3.62$, $SD = 1.08$) than it is for the steps of separation [$M = 3.44$, $SD = 1.14$, $F(1, 542) = 7.96$, $p < 0.001$, partial $\eta^2 = 0.03$] and purification of CO_2 [$M = 3.48$, $SD = 1.09$,

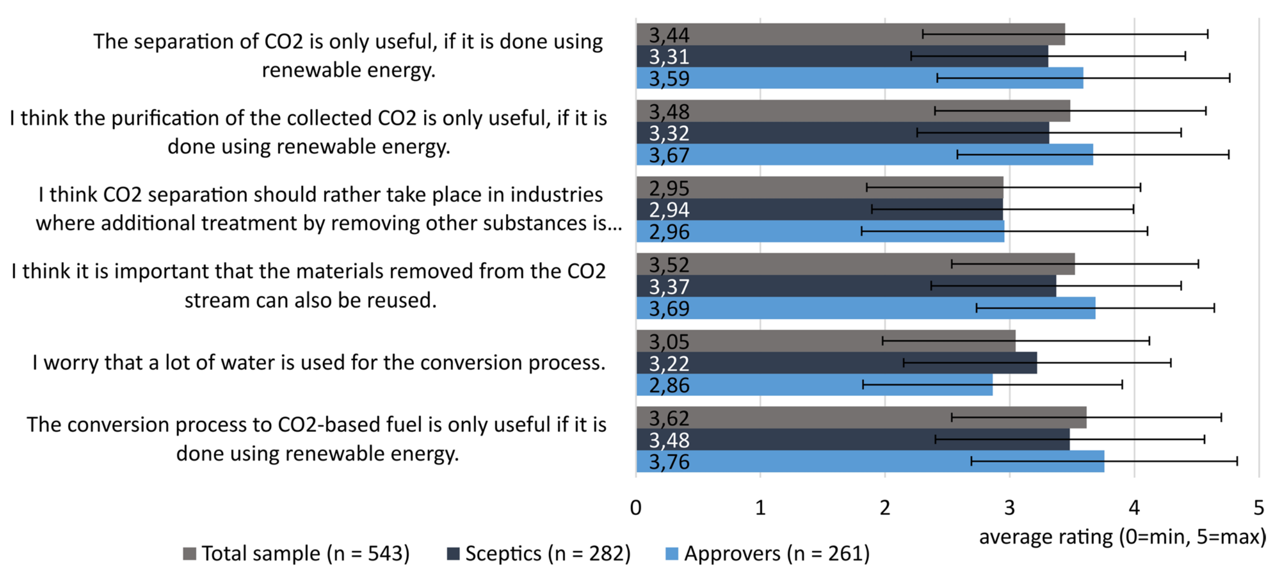

Fig. 4 Average ratings for *perception of material and energy utilization* for total sample, Sceptics, and Approvers

$F(1, 542) = 4.64$, $p < 0.001$, partial $\eta^2 = 0.02$]. Interpreting partial η^2 according to Cohen (1988), these are differences with medium effect [81].

There is, in contrast, unanimity for the statement that CO_2 should preferably take place in industrial sectors, where there is no need for further treatment of the CO_2 [$M_{Appr} = 2.96$, $SD = 1.15$, $M_{Scept} = 2.94$, $SD = 1.05$, $t(260) = -0.16$, n. s.]. Across the sample, people are more likely to agree that further purification could be avoided by performing CCU in plants with a purer CO_2 stream [$t(542) = 9.57$, $p < 0.001$, $d = 0.41$]. The following was determined for the use of the substances separated during purification and for the use of water during conversion to hydrocarbons: Approvers ($M = 3.69$, $SD = 0.95$) significantly agreed more than Sceptics with the statement that re-usability of separated materials is of importance [$M = 3.37$, $SD = 1.00$, $t(541) = -3.73$, $p < 0.001$, $d = -0.32$]. Simultaneously, Approvers were less concerned about the increased usage of water during conversion into hydrocarbons ($M = 2.86$, $SD = 1.04$) than Sceptics [$M = 3.22$, $SD = 1.07$, $t(541) = 3.94$, $p < 0.001$, $d = 0.34$]. However, both groups are rather concerned about water usage than not, as even the mean agreement of Approvers still significantly differs from the mid-point of the scale (2.5) [$t(281) = 7.1$, $p < 0.001$, $d = 0.42$].

Perception of plant conditions

The second group of items identified using factor analysis concerns *perception of plant conditions*, e.g., "I think the purification of CO_2 is a useful step if this ensures the longevity of the production plant."

As is evident from the visual analysis of Fig. 5, the differences between the two clusters are greater for the perception of plant conditions. Sceptics significantly less supported the premise that CO_2 is being separated from streams in the first place instead of being released into the atmosphere ($M = 3.32$, $SD = 1.12$) than Approvers [$M = 4.22$, $SD = 0.84$, $t(518.21) = -10.72$, $p < 0.001$, $d =$ -0.91]. The perception of separation of CO_2 at its point of origin being a good thing [$M_{Appr} = 4.02$, $SD = 0.91$, $M_{Scep} = 3.02$, $SD = 1.04$, $t(541) = -11.84$, $p < 0.001$, $d = -1.02$] as well as the perception that it is the better option compared to DAC [$M_{Appr} = 3.86$, $SD = 0.92$, $M_{Scep} = 3.03$, $SD = 1.15$, $t(541) = -9.19$, $p < 0.001$, $d = -0.79$] were significantly lower in Sceptics. Another aspect in connection with plant circumstances is the requirement of purification being a way to ensure plant longevity, which was also significantly different between the two clusters [$M_{Appr} = 3.78$, $SD = 0.9$, $M_{Scep} = 3.02$, $SD = 0.95$, $t(540.67) =$ -9.63, $p < 0.001$, $d = -0.83$]. In the case of the (sometimes necessary) step of purification of the CO_2 stream, it is more important to Approvers ($M = 4.11$, $SD = 0.82$) than it is to Sceptics ($M = 3.41$,

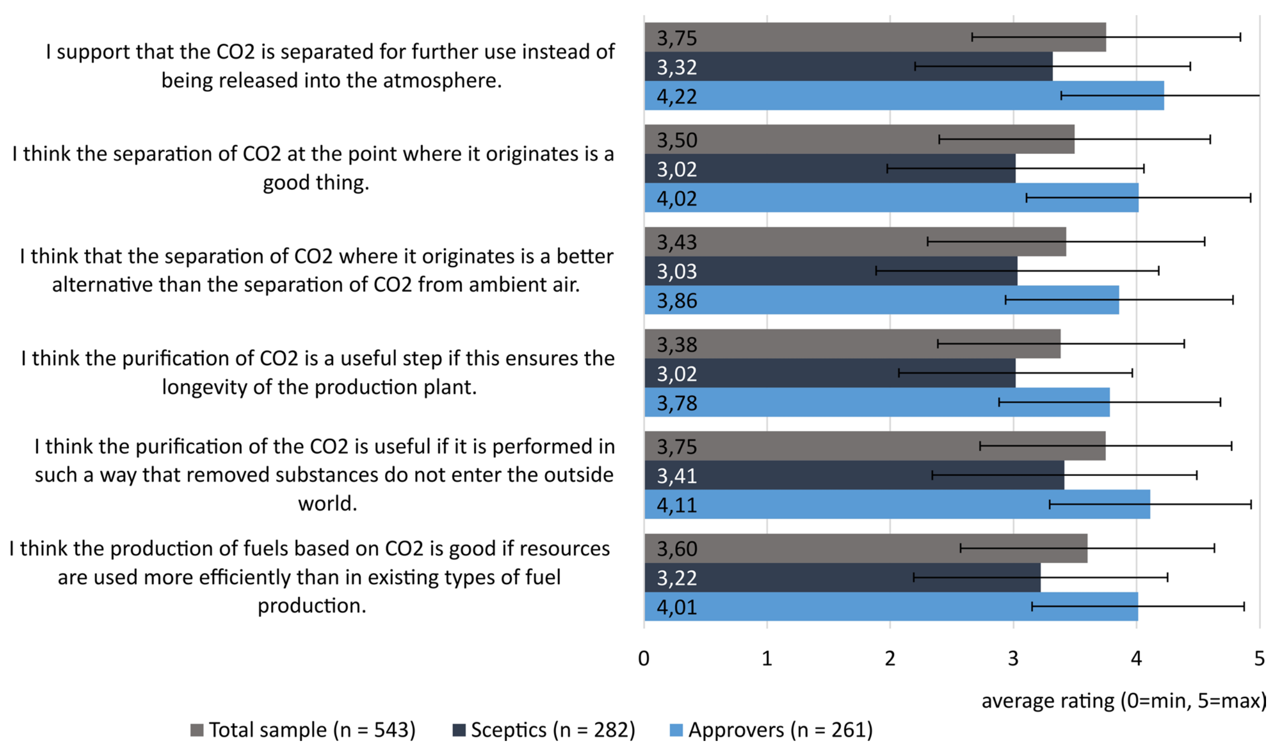

Fig. 5 Average ratings for *perception of plant conditions* for total sample, Sceptics, and Approvers

$SD = 1.08$) that the substances filtered out are subsequently handled in such a way that they cannot enter the environment [$t(521.81) = -8.53$, $p < 0.001$, $d = -0.73$]. Finally, it can be stated that the condition of an efficient use of resources, making the production perceived as favorable in comparison to conventional fuel production, plays a greater role for Approvers ($M = 4.01$, $SD = 0.86$) than for Sceptics [$M = 3.22$, $SD = 1.03$, $t(535.57) = -9.74$, $p < 0.001$, $d = -0.83$]. All in all, however, it must also be noted that both groups agreed or strongly agreed with the items examined, as all answers differed significantly on average from the center of the scale.

Discussion

In this research, we focused on public perceptions and acceptance evaluations of the process steps necessary to produce CO_2-based jet fuels. The novelty of the approach is the analysis of public perceptions of four different steps in the production process—separation, purification, transport, and conversion. This way, we connect to the finding that the perception of the CCU technology can impact the acceptance of CO_2-based fuel not only regarding the manufactured end-product [16] but identify possible acceptance hot spots among the necessary production steps. Furthermore, as consumers are typically diverse in their perceptions and acceptance judgements, we explore which (user) factors influence the public perception of the involved steps of the production of CO_2-based jet fuels. The identification of two acceptance clusters or segments led to detailed insights in differences in technology evaluations and plant roll-out requirements.

Breaking down the production process of CO_2-based jet fuel—one of these things is not like the others (RQ 1)

A direct comparison of the production steps related to CCU for CO_2-based fuel production revealed that there are significant differences in people's assessment of the capture, purification, transport, and conversion of CO_2. Specifically, *transport of* CO_2 showed a distinctive profile of perceived attributes in comparison to the other production steps. It is perceived to be significantly less acceptable and useful, and more damaging for the environment and health while also being perceived as more expensive. As for perceived efficiency, transport was perceived to be significantly less efficient than capture, purification, and conversion of CO_2. On average, however, respondents' evaluation in this regard were inconclusive, meaning there was no evident tendency towards efficiency or inefficiency. Transport being assessed differently is consistent with previous results, as risks were investigated more frequently for transport [14, 76]. However, as previously highlighted, there is a general lack of studies that specifically investigate the perception of the different CCU production steps. Therefore, the absence of results regarding risk perception cannot directly infer a lower perception of risks.

It is important to consider that the instruction given to respondents did not mention a specific transportation mode. This was done to prevent framing respondents by giving them multiple options causing them to think of a specific case and then transferring their mental models of this specific mode for their answers, without the option for us to check afterwards which mode of transport they specifically considered. The instruction related to the length of the transport, as the conversion process could occur either on-site or through short to long-range transport to another location. Considering that the participants were aware of this distinction, the evaluation profile suggests that, from their perspective, conversion should ideally occur directly on-site. This finding aligns with the participants' perception of lower acceptability and usefulness of CO_2 transport, as well as their uncertainty regarding the perceived efficiency of this process step and confirms earlier findings [56].

Furthermore, it is noteworthy that the other production steps did not show significant differences from each other in terms of public perceptions. This lack of difference could be attributed to their technical nature, as the explanations provided were kept brief and designed to be as layperson friendly as possible. In contrast, the concept of transport, being the most tangible step, is one that people may have encountered in their personal lives or through media reports of transportation of goods via pipelines or roads.

Moreover, while the three steps of the production process are generally perceived as acceptable, useful, efficient, environmentally friendly, and not harmful to health, there is still room for improvement in their evaluation. This may indicate a certain degree of skepticism among participants, which could be attributed to factors such as limited knowledge about the technology and its mode of operation (as measured in this study and other sources) [62, 71, 82]. In addition, it is possible that concerns about the sustainability of the technology [16] are reflected in the evaluation of individual steps.

Hence, based on these findings, it can be concluded that there is potential for providing more information to enhance people's understanding of the technology. Previous studies regarding CCU acceptance report low levels of public information and knowledge about CCU [62, 83], at least in European countries. While this is a clear call to action and strong evidence to convey knowledge to the public and to create awareness for novel renewable energy technologies in the fuel aviation sector, such information provision can serve to highlight that this technology, along with other alternatives, has the potential to contribute to a more sustainable aviation transport sector without detracting from efforts and research in other areas. Still, we should be clear that the mere increase of public information does not necessarily increase acceptance. Previous research in this context highlighted that consumers are quite diverse in their reception of technical information [84–86]. For users that already have a basic understanding of the technical approach, more information might be helpful [87], while people that only have a rudimentary knowledge base their (non-)acceptance reactions on affective evaluations that are related to (dis)trust [88]. Thus, information and public education strategies should be developed with care and in line with the specific information requirements of the public and potential consumers [89, 90]. Attention must also be paid to attitudinal characteristics (e.g., CO_2 knowledge, environmental awareness) that are recognized as being interrelated, as was the case with our sample (see Table 2).

Predictors of attitude towards production steps—the prominent role of risk perception (RQ 2)

The answers to RQ 2.1–2.4 can be combined to draw a comparative in-depth picture of the whole CO_2-based jet fuel production process.

Interpreting the results of regression analyses, we find that the influence of technology perception on people's attitude of all four production steps is remarkable. The influence of CCU benefit and barrier perceptions is in accordance with previous research [16, 62, 64] while confirming to be a relevant factor even on a more detailed technology assessment level. When interpreting the standardized betas, the perceived benefits (e.g., "CCU contributes to saving fossil resources.") have an even stronger influence than the barriers (e.g., "CCU only delays the problem of increased CO_2 emissions."). Notably, only in the case of purification of CO_2, the positive influence of benefit perception on attitude is nearly as strong as the negative influence of perceived risks. This finding is remarkable, especially considering the clear differences observed in the dimensions examined in RQ 1. This result also contradicts previous findings that hinted at perceived production step risks not having a significant impact on CCU acceptance [62]. It can be assumed that the relatively low knowledge about the CCU technology is accompanied by a certain level of skepticism and may influence the perception of risk—which should be investigated in future studies. An increased risk perception for the CO_2 transport step has already been observed in previous literature [14, 76]. This was confirmed here. Although the risk perception for transport is highest compared to the other steps, the strong influence in the case of conversion, capture, and purification is a new finding.

For the overall sample, the descriptive analysis of risk perception per step (see Table 1) shows that CO_2 purification was perceived as the step with the least associated risks. Separation and conversion of CO_2 were also perceived as relatively low in risks. This lower perception of risks could be due to various reasons. Limited awareness of the process itself may lead to a perception of low risks (regardless of whether actual risks are high or low). In addition, lack of experience with these highly technical and not directly perceivable steps, from a layperson's perspective, may result in individuals not perceiving increased risks. This aligns with the comparatively higher perception of risks in transportation, which is the most tangible step among the four for which individuals may draw upon experiences and reports from other transportation modes.

When interpreting results for the identified clusters, we also observed significant differences between the identified Approvers and Sceptics (see Table 3). Given that it has been established that risk perception is a strong influencing factor in the case of all production step attitudes, it is not surprising to see significant differences in this regard. However, this implies that there is room for specific communication strategies, for example, to address the differences between the two groups and to tailor information efforts accordingly. In the case of user factors identified as predictors of attitude towards the production steps, a diverse pattern emerges. For the step of CO_2 separation, it was found that women (similar to the case of factors influencing the attitude towards CO_2 transport) and individuals with an increased knowledge of the chemical properties of CO_2 tend to perceive this step more positively. This finding contradicts a previous study [66]. As this factor was not identified as an influential factor for the remaining steps it is highlighted that a step-wise analysis of the whole process allows for a deeper understanding of attitude-influencing factors.

The openness to innovation was also identified as a positive influencing factor for the steps of purification and conversion. In the direct comparison of these more abstract process steps, for which chemical processes are central, being open to technological innovation has a positive impact. Finally, a difference was observed in the case of education: for the CO_2 transport step, individuals with higher education rated this step more negatively compared to those with a medium level of education. Interestingly, no influence of awareness was observed. Similarly, Arning et al. [71] observed no impact on fuel acceptance by subjective knowledge on the matter, but a minor influence by people's stated interest [71]. Similarly, environmental consciousness and knowledge of the

Table 3 Descriptive and inferential statistics for Cluster 1 and 2 for user characteristics and technology perceptions

Factor	Cluster 1 (n = 282)	Cluster 2 (n = 261)	t	p	d
User characteristics					
Age [M (SD)]	43.06 (14.92)	47.09 (15.17)	$t(541) = -3.12$	0.002	−0.27
Gender [%]*				n. s	
Female	51.1	48.7			
Male	48.9	51.3			
Education [%]*				n. s	
Low	17.0	14.6			
Medium	54.3	56.7			
High	28.7	28.7			
Environmental awareness [M (SD)]	3.32 (0.96)	3.53 (0.86)	$t(541) = -2.78$	0.006	−0.24
Openness to innovation [M (SD)]	2.27 (0.87)	2.42 (0.86)	$t(541) = -2.04$	0.042	−0.18
CO_2 chemical knowledge [M (SD)]	2.79 (1.11)	3.08 (1.32)	$t(470.20) = -2.68$	0.008	−0.24
CO_2 effect knowledge [M (SD)]	3.80 (0.80)	3.88 (0.75)		n. s	
Technology perception					
Awareness of CO_2-based jet fuel production [M (SD)]	0.84 (0.98)	0.99 (1.07)		n. s	
Attitude towards CO_2 separation [M (SD)]	2.39 (0.95)	3.80 (0.71)	$t(518.00) = -19.86$	< 0.001	−1.67
Attitude towards CO_2 purification [M (SD)]	2.49 (0.78)	3.81 (0.58)	$t(517.04) = -22.41$	< 0.001	−1.90
Attitude towards CO_2 transport [M (SD)]	2.01 (0.87)	3.08 (0.93)	$t(541) = -13.89$	< 0.001	−1.19
Attitude towards CO_2 conversion [M (SD)]	2.41 (0.81)	3.78 (0.60)	$t(515.92) = -22.51$	< 0.001	−1.91
Risk perception for separation of CO_2 [M (SD)]	2.46 (0.94)	1.58 (0.83)	$t(541) = 11.50$	< 0.001	0.99
Risk perception for purification of CO_2 [M (SD)]	2.11 (1.04)	1.26 (0.86)	$t(541) = -10.32$	< 0.001	−0.89
Risk perception for transport of CO_2 [M (SD)]	2.88 (0.81)	2.24 (0.89)	$t(525.58) = 8.73$	< 0.001	0.75
Risk perception for conversion of CO_2 [M (SD)]	2.77 (0.80)	1.88 (0.76)	$t(541) = 13.20$	< 0.001	1.13
CCU benefit perception [M (SD)]	2.71 (0.80)	3.49 (0.69)	$t(541) = -12.03$	< 0.001	−1.03
CCU barrier perception [M (SD)]	2.93 (0.74)	2.41 (0.73)	$t(541) = 8.26$	< 0.001	0.71

*χ^2 was calculated for nominal data, but test statistics are not reported due to lack of significance

impacts of CO_2 did not play a significant role, which differs from previous research [71, 72, 91].

Thus, the CCU production step-specific examination of user-related factors reveals a more diverse picture. This insight should be considered when developing information materials about CCU. While there are impacts by risk, benefit, and barrier perception across the steps, the differences in user factors and their different receptiveness for technological innovations indicate that the perception of individual steps may vary among different individuals, influenced by factors such as education, CO_2 chemical knowledge, gender, and openness to innovation.

In-depth analysis of CCU production roll-out requirements—Disagreements and same destinations (RQ 3)

We addressed the last research question of the study by examining whether distinct groups of individuals could be identified in the data set based on their evaluation of the production steps. In the subsequent step, we examined how these groups differ in their evaluation of production requirements.

One result in the context of the CCU production requirements is the identification of two main topics: *Perception of material and energy utilization* and *Perception of plant conditions*. The descriptive results for the items in the former group clearly indicate that sustainability is a relevant aspect of CCU production, as respondents' answers reveal the importance of the use of resources (such as energy or water). This is in line with previous research that reveals sustainability concerns or perceived sustainability barriers as decisive acceptance-relevant factors [16, 70]. It becomes clear that not only the reuse of CO_2 by CCU, but the sustainability of other process elements is a requirement for laypeople.

The results of the cluster analyses show that Approvers (those with a more positive attitude towards CCU production steps) are more likely to agree that the use of renewable energy is essential in the steps of separation, purification, and conversion of CO_2 compared to Sceptics. This suggests that policies promoting the use of renewable energy in CCU production steps may be more appealing to those who are more positively inclined towards CCU. Therefore, policy initiatives that prioritize and incentivize the use of renewable energy in CCU processes may help foster support from those who are already inclined towards CCU, while also addressing concerns of environmental sustainability. Further implications from the results regarding perception of material and energy utilization are the promotion of the re-usability of separated materials and addressing concerns about water usage. Although these are not highly elevated concerns in both groups, when communicating about CCU, these potential concerns and barriers should also be addressed. This way, for both regional and national implementation strategies, the public can be enabled to come to informed decision-making [65].

For the statements concerning the perception of plant conditions, additional implications can be concluded from the results. In this regard, the already mentioned requirement of sustainability plays a role as well (e.g., in the context of plant longevity); however, a closer interpretation of item contents of the statements categorized in this item battery (based on factor analysis) shows that the implementation of CCU into industrial environments is also perceived as a preventive measure. Participants (in case of Approvers more prominently) agree that separation and further processing of CO_2 should be conducted to prevent emissions or other substances to be released into the atmosphere. Furthermore, efficiency of CCU-based fuel production could be identified to be very relevant to Approvers. Taking into consideration that this group on average shows a higher level of openness to innovation, we can conclude from these results that although the knowledge on CCU is rather low, the public is nevertheless interested in technology aspects of climate-friendly technologies other than sustainability.

Based on Sceptics' lower agreement to the production related requirements, communication efforts should focus on addressing concerns of this group. More specifically, understandable information about the benefits and advantages of separation of CO_2 at its point of origin and on the effectiveness and sustainability of the production process should be provided. In addition, existing technical measures to ensure effectiveness and optimal utilization of separated CO_2 should also be communicated. Although there is overall agreement and therefore a form of consensus in both groups, there are still significant differences, highlighting the potential for further public information.

Methodological limitations and future research

While our study provides valuable insights into the perception of CCU production steps to produce CO_2-based jet fuel, it is important to note that no study is without limitations.

One limitation is that the subject matter is highly technical, and we cannot simply assume that laypeople easily grasp the depth of the technical topic. Still, we took great care to present the topic and the instructions in a lay-friendly manner through the gradual provision of concise information. Nonetheless, we cannot quantify the depth of understanding of the technology, or whether the respondents' cognitive processing of information relied on mental models that might have influenced the results, but we should be aware that this is in fact also the case when laypeople form their opinions on the technical level they have. In addition, in this context, the risk of pseudo-opinions needs to be considered, as attitudes towards new and highly technical topics may not be stable. While the information material was carefully selected, pseudo-opinions and their impact on the results cannot be entirely ruled out.

There are additionally still several paths for future research that could build upon and extend our findings. For instance, a potential next step could be to investigate the acceptance and usage intention of CO_2-based jet fuel and their relationship with the perception of the individual CCU production steps. This effort would have exceeded the scope of the current study. In addition, in future studies, the scope of production perception analysis of technological approaches such as CCU could be broadened further by embedding them in a systematic approach. Further insights could be obtained, for example, by analyzing public perception of aspects such as energy efficiency and the use of resources in a multi-technology portfolio to combat climate change. However, this requires careful consideration of the depth of information in studies with laypeople and of the chances of reliable measurements at this level of complexity.

Moreover, our investigation focused on the socio-political dimension according to Wüstenhagen et al. [61]. From other studies that focus on local acceptance we know that local perception and acceptance can differ significantly from general perception and acceptance of technological infrastructure [92–94]. This needs to be investigated in future studies to determine whether proximity to production and transport infrastructure is another influencing factor and whether the results obtained here remain consistent for a local scenario.

Finally, it can be noted that the proportion of explained variance was already quite high for explaining the perception of individual steps. However, there is still room for investigating further influential factors on perception. Future studies should aim to identify further attitude-influencing factors and their impact.

Impact of the findings for policy makers and public communication strategies

The aviation sector is actively pursuing decarbonization with strategies like fleet renewal, implementing disruptive propulsion technologies, enhancing operational efficiency, and increasing sustainable aviation fuel (SAF) usage. An ambitious target set for this sector is achieving net-zero emissions by 2050, balancing the growth in air travel demand with the urgent need to reduce its carbon footprint. Development and adoption of renewable electricity, technological breakthroughs, and alternative technologies, including hydrogen and electric propulsion, are also central to this effort. Importantly, public perception plays a critical role in the success of these strategies, as societal acceptance and regulatory support are essential for implementing new technologies and practices. Future research must, therefore, also focus on understanding public perception towards these decarbonization strategies.

The contribution of this study to the current discussion on decarbonization in both public and policy-making spheres is based on awareness of the public's acceptance requirements and the need for transparency in the public (policy) communication. Understanding acceptance can aid in identifying specific groups of accepters and non-accepters, as well as the pros and cons that the public associates with such innovations. This information can be used to shape effective information and communication strategies on the one hand but also to inform policymakers and communal deciders about the importance of launching an open-minded policy communication that helps the public to gain knowledge about novel decarbonization efforts and their role in combating climate threats.

Policy makers and technical developers should be aware that the public is not a homogeneous group. Different groups may perceive risks associated with CCU production steps differently based on their experience and attitudes. This goes both ways: for example, for groups with more positive attitudes towards CCU, emphasizing potential risks and uncertainties may be necessary to provide a balanced understanding of the technology, while for groups with more negative attitudes, highlighting potential benefits and addressing concerns may be more effective in building trust and acceptance. This result furthermore highlights the importance of conducting a thorough risk assessment not only for safe production but also for effective communication. It is particularly important to communicate safety measures and precautions for production steps that involve a high risk perception, such as the transport of CO_2, as this can influence public attitudes towards risk. There is a need to provide the general public with accurate information regarding the actual risks associated with the technology. This will enable individuals to make informed decisions based on factual knowledge rather than assumptions. The low level of awareness highlights the need for such information.

We therefore have a great responsibility to develop appropriate science communication and information pathways that are accessible to the general public and that help fill the knowledge gaps the public have in an objective and transparent way. Overall, it is highly valuable to capture public opinion to inform the technical design about possible barriers to acceptance, and at the same time to systematically inform the diversity of the public about the benefits and barriers of innovations. In this way, we create a solid foundation for people without technical expertise to make informed decisions.

Conclusions

As a novelty in acceptance research towards CO_2-based jet fuel innovations, the present study presents an investigation on people's perceptions of the different steps involved in CCU production for CO_2-based jet fuel. We found that there were significant differences in people's assessment of the capture, purification, transport, and conversion of CO_2, with transport being the least positively perceived step. The study also found that people's attitudes towards the different steps were influenced by their perceptions of the benefits and barriers of CCU technology, as well as their perception of the risks involved in each step. Furthermore, our findings highlight the importance of knowledge and education in shaping attitudes towards new technologies. For example, individuals with a better understanding of the chemical properties of CO_2 may be better equipped to understand the technical aspects of the CO_2 separation step. Our results also suggest that there is a need to provide more accurate information to the public to enhance their understanding of the technology and address concerns about its sustainability.

Overall, the study's findings underscore the complex interplay between (perceived) technical, environmental, and user-related factors that shape public attitudes towards new technologies. By shedding light on the specific factors that influence attitudes towards CCU technology, this study provides important insights that can inform efforts to promote the development and adoption of sustainable aviation fuels.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13705-024-00441-8.

Additional file 1: Table S1. Descriptive statistics for constructs included in regression analyses. **Table S2.** Post-Hoc-Bonferroni test

'Unacceptable–Acceptable' for all production steps. **Table S3.** Post-Hoc-Bonferroni test 'Not useful–Useful' for all production steps. **Table S4.** Post-Hoc-Bonferroni test 'Damaging for the environment–Environmentally friendly' for all production steps. **Table S5.** Post-Hoc-Bonferroni test 'Inefficient–Efficient' for all production steps. **Table S6.** Post-Hoc-Bonferroni test 'Expensive–Cheap' for all production steps. **Table S7.** Post-Hoc-Bonferroni test ,Health damaging–Not health damaging' for all production steps. **Table S8.** Step-wise multiple linear regression model for attitude towards separation of CO_2. Adj. $R^2=0.460$, Durbin-Watson = 1.76, N = 491). **Table S9.** Step-wise multiple linear regression model for attitude towards purification of CO_2. Adj. $R^2=0.462$, Durbin-Watson = 2.05, N = 491). **Table S10.** Step-wise multiple linear regression model for attitude towards transport of CO_2. Adj. $R^2=0.384$, Durbin-Watson = 2.07, N = 491). **Table S11.** Step-wise multiple linear regression model for attitude towards conversion of CO_2. Adj. $R^2=0.499$, Durbin-Watson = 2.00, N = 491). **Table S12.** Step-wise multiple linear regression model for the evaluation of CO_2-based jet fuel. Adj. $R^2=0.701$, Durbin-Watson = 2.30, N = 491). **Table S13.** Post-Hoc-Bonferroni test risk perceptions for all production steps.

Author contributions
LE: empirical design, data collection and analysis, writing original draft, visualization. KA: empirical design, data collection, review and editing of draft. MZ: review and editing of draft, funding acquisition, project administration.

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

Declarations

Ethics approval and consent to participate
For this study involving human participants, the structure, contents, and data management of the used instrument were checked by the Ethics Committee of the Faculty of Arts and Humanities at RWTH Aachen University and were approved for empirical use. Before starting the survey, participants were informed about the aims of the study and about data being collected anonymously. They also were briefed about them being able to end their participation anytime. The participants provided their written informed consent to participate in this study.

Competing interests
The authors have no competing interests of financial or personal nature that might be perceived to influence the results and/or discussion reported in this paper.

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