Energy Reports 13 (2025) 5463–5473

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research Paper

Public discourse on CO_2 transformation technologies: Lessons from a German study

Linda Engelmann *, Julia Offermann, Martina Ziefle

Chair of Communication Science, RWTH Aachen University, Germany

A R T I C L E I N F O

Keywords:
Social acceptance
CO_2-based fuel
Public perception
Information needs
Communication
Carbon capture

A B S T R A C T

In the context of climate change, emission intensive sectors such as aviation face the need to mitigate environmental impacts while demand is still rising. The use of CO_2-based fuel offers the opportunity to make flight travel less carbon intensive. Understanding public perception of technological approaches like CO_2-based jet fueled travel plays a pivotal role in enabling the integration of sustainable technologies. To explore how to communicate about CO_2-based aviation fuel, we used a mixed-method approach. Following qualitative interviews (n = 12) to identify relevant elements in lay communication, a subsequent online survey of n = 152 participants was carried out to quantify the results. The analysis of the collected data identified various public information needs, such as information about CO_2-based fuel's sustainability, development, and production. Furthermore, we discovered that factors such as communicator preference, as well as information content and preparation are linked to user characteristics such as environmental awareness, and attitudes towards flying as a mode of transportation. Recommendations for recipient-oriented communication strategies can be formulated based on these results.

1. Introduction

1.1. Motivation

In the context of climate change the need for more sustainable modes of transportation and travel is growing. Aviation made up 2 % of global emissions in the year 2022 (IEA, 2022), with growing numbers of flight passengers in the last years, despite a dip in air travel due to the COVID-19 pandemic (Eurostat, 2025). Sustainable aviation fuel such as CO_2-based fuel produced from hydrogen, carbon dioxide, and electricity has the potential to significantly reduce the environmental impact of the aviation sector (Barke et al., 2022). However, the production of CO_2-based fuel can be energy-intensive and costly, and it requires an electricity mix based on renewable energies to achieve significant reductions (Schmidt et al., 2018). Furthermore, regulatory intervention on a national level is needed, as only a limited number of nations has developed comprehensive legal frameworks facilitating the adoption of fuel alternatives, although the Renewable Energy Directive II acknowledged their inclusion in 2018 (Skov and Schneider, 2022).

Public perception of sustainable technologies is crucial for their successful adoption and deployment (Boudet, 2019). This is also true for the integration of new fuel types in the market, which can be dependent on consumer acceptance, as is evident by the introduction of and the public's hesitation towards E10 in Germany (Tosun, 2018). When it comes to the specific case of aviation fuel, the situation is different from that of car fuel, as it is not refilled by the passenger as the end user. However, the general public's attitude towards this more sustainable type of fuel can be reflected in perceptions and people's willingness to fly on an airplane fueled with an innovative fuel technology. Furthermore, public opinion can impact policy making (Burstein, 2003) and therefore, understanding public attitudes, concerns, and misconceptions surrounding innovations is an important aspect that needs to be considered on different levels of technology introduction.

This paper therefore aims to provide a comprehensive analysis of public perception regarding CO_2-based fuel use in aviation, highlighting the factors that shape attitudes towards their adoption as well as analyzing distinct adoption groups.

1.2. Related research

1.2.1. Carbon capture and utilization and production of CO_2-based jet fuel

The approach to sequester CO_2 from the atmosphere arose from the

* Corresponding author.
E-mail address: engelmann@comm.rwth-aachen.de (L. Engelmann).

https://doi.org/10.1016/j.egyr.2025.05.008
Received 5 February 2025; Received in revised form 10 April 2025; Accepted 6 May 2025
Available online 10 May 2025

pressing need to reach climate goals in order to mitigate consequences to the climate as well as flora and fauna. CO_2-based fuels for the aviation sector are one of several products that can be obtained based on Carbon Capture and Utilization (CCU), a technological approach enabling the production of added value products with sequestered CO_2 (Nocito and Dibenedetto, 2020). Another related approach is the underground storage of CO_2 in geological formation. Depending on the source of CO_2, these approaches are considered as negative emission technologies. For Direct Air Carbon Capture and Storage (DACCS), the CO_2 is separated for example from ambient air under the use of low-carbon energy sources (e.g., solar energy) (Küng et al., 2023). Cases in which CO_2 is separated at a high emission source such as an industrial plant and afterwards is stored underground are not considered carbon negative as they only prevent emissions reaching the atmosphere (Desport and Selosse, 2022). Nonetheless, life cycle assessment indicates that certain CCU processes can lead to net reductions in environmental impacts, particularly when the captured CO_2 is used to produce long-lasting products or when the processes are powered by renewable energy sources (Al-Mamoori et al., 2017; Thonemann and Pizzol, 2019).

For the purpose of the manufacturing of products, CO_2 is captured, e.g., at an industrial point-source or via Direct Air Capture (Galimova et al., 2022), by means of membranes, adsorption or (physical or chemical) absorption (Hasan et al., 2015). After the removal of impurities in a purification step (if necessary) (Abbas et al., 2013), the CO_2 is converted, for example, into CO_2-based fuels. Methanol or dimethyl ether production as well as Fischer-Tropsch synthesis are potential routes of production, converting CO_2 into hydrocarbons under the use of water and renewable energy (Dieterich et al., 2020). Depending on the place of separation and conversion, it can be necessary to transport i) the separated CO_2 to the place where it will be synthesized as well as ii) intermediate or end-products to their place of consumption. The impact of these transport routes has to be considered in life cycle analyses to assess the environmental impact of the production process in its entirety (Rojas-Michaga et al., 2023). The need for a sufficient supply of electricity from renewable sources leads to the production of CO_2-based fuel being in competition with other sectors that have a demand for renewables. Other hurdles to be overcome on the way to the adoption of CO_2-based aviation fuel are high production costs and necessary technological progress to raise the technology to a higher technology readiness level (Ozkan et al., 2024). However, sustainable aviation fuels are evaluated as an essential element for aviation to reach societal goals such as the UN Sustainable Development Goals (Raman et al., 2024). Furthermore, for heavy transport sectors such as aviation whose fleet wide electrification is not yet in reach (IEA, 2022), CO_2-based fuel creates an opening for a less emission intensive modus operandi, as life cycle analysis shows that the global warming potential of CO_2-based fuel is lower than for conventionally produced kerosene (Rojas-Michaga et al., 2023).

1.2.2. Acceptance and perception of CO_2-based jet fuel

Actively or passively approving a technology or product such as CO_2-based jet fuel – as well as the circumstances in which it is developed, implemented, or used – can be defined as *technology acceptance* (Dethloff, 2004). Wüstenhagen et al. (2007) divide the concept of acceptance into three dimensions. Contrary to community acceptance (i.e., acceptance of siting by local residents) and market acceptance (i.e., market adoption of a product or technology), this study focuses on what was conceptualized as socio-political acceptance, i.e., general acceptance by different stakeholders like the public, on a broader level (Wüstenhagen et al., 2007). A prominent predictor of technology acceptance is *public perception*. Perceptions of costs, risks, and benefits have been found to influence people's attitudes and (indirectly) their acceptance of sustainable energy technologies (Huijts et al., 2012).

The results on acceptance of CO_2-based fuel (for its use in the aviation industry) are still rather limited but continue to grow. In previous studies, CCU as the technological approach underlying CO_2-based fuel production was positively perceived due to the utilization of CO_2 in terms of its general potential for combating climate change and in connection with benefits relating to job creation and the added value through the reuse of CO_2. Negative associations with CCU related to risks of halting necessary behavioral changes or delaying investments in (from a lay perspective potentially) more promising technologies (Jones et al., 2015). The acceptance of CCU (Oltra et al., 2022) in general, of CCU products (Lutzke and Árvai, 2021), and of related production steps (Engelmann et al., 2024) was found to be rather high.

The production of CO_2-based fuel as a specific production route following the separation and conversion of CO_2 also has been the object of investigation in previous acceptance studies. In a comparative study on bio- and CO_2-based fuel perception Linzenich et al. (2023) found that both fuel types "were perceived as useful, environmentally friendly, safe to use, and to have a low CO_2 footprint" (Linzenich et al., 2023) and that CO_2-based fuels were estimated to be causing higher costs (Linzenich et al., 2023). In a study on car drivers and their acceptance of CO_2-based fuel, Bergfeld et al. (2023) observed that for people with higher levels of environmental awareness characteristics of the fuel, such as CO_2 emissions and the resource utilization, were of higher relevance (Bergfeld et al., 2023). Interestingly, further research indicates that there is no difference between road and aviation application of CO_2-based fuel in regard to general acceptance or behavioral intention to drive/fly with an CO_2-based fueled vessel (Engelmann et al., 2020). For the specific case of CO_2-based jet fuel, acceptance was observed to be rather high and was influenced by people's interest in the topic, their environmental awareness, flight shame, as well as benefit perceptions and risk perceptions (e.g., referring to health and the environment and technical quality and maturity of the fuel) (Arning et al., 2023). Previous research furthermore revealed that flying as a mode of transport is predicted by a person's attitude towards flying. Additionally, in the context of aviation, the problem awareness of the environmental impact of flying significantly predicts the perceived dilemma between environmental attitudes and behavior (Oswald and Ernst, 2021). Further research needs to be conducted to check for a connection between environmental problem awareness and openness to sustainable technologies in the aviation sector.

1.2.3. Informing and communicating about sustainable innovation

A study on the acceptance of the life cycle of CO_2-based fuel illustrated that different levels of information on sustainable technologies or products and their production can impact how laypeople perceive said objects of evaluation. Offermann-van Heek et al. (2020) found that, for the production of CO_2-based fuel, the assessment of the type of CO_2 source as well as of the fuel production plant size changed after participants in an online survey received more in-depth information on these aspects (Offermann-van Heek et al., 2020). Research on the topic of *how* to inform and communicate about sustainable technologies and products is limited. A relevant phenomenon related to this question of *how* is the knowledge-behavior-gap, which describes a lack of behavioral change in line with a rather sustainable consciousness. It is a circumstance that has been studied in the context of environmentally conscious behavior, among others (ElHaffar et al., 2020; McDonald et al., 2015). It is therefore disputable whether more information will lead to more environmentally conscious behavior, and if and to what extent further information on innovations such as CO_2-based jet fuel can bring about a change in behavior. Furthermore, regarding the acceptance of a sustainable technology analyzed in this study, it is necessary to refrain from understanding the provision of information for the purpose of boosting acceptance artificially and intentionally. However, previous research has identified awareness of a technology to be an impacting factor for acceptance (Liu et al., 2013). Furthermore, a study by Goodarzi et al. (2021) on the intention to use photovoltaic systems observed that the number of sources consulted positively influenced behavior adoption intentions, as did access to customized information on a technology for respondents, that were already interested in the technology (Goodarzi et al., 2021). Furthermore, research indicates that the source of information as well as trust in providers of information has the potential to impact environmentally friendly behavior (D'Amato et al., 2019). Therefore, it is argued in this study that it is necessary to investigate informative needs and communicative preferences of laypeople to enable and foster informed formation of attitudes and informed decision making.

1.3. Research questions

In order to address the above issues of acceptance, perception and communication of CO2-based aviation fuels, we formulate research questions to exploratively identify acceptance factors and to inferentially analyze relationships with acceptance and user factors.

The first aim of this study is to filter out the underlying dimensions of lay perceptions from a set of positive and negative associations with CO_2-based jet fuel. This analysis will help determine the key factors that are relevant to lay perceptions. Therefore, we pose the following research question (RQ): *RQ1: Which factors can be identified in laypeople's perception of CO_2-based jet fuel?*

Previous research modelling the acceptance of sustainable technology indicates that the factors impacting acceptance can be manifold (e.g., Huijts et al., 2012). In a second step, it is therefore useful to investigate which of the factors identified in the exploratory analysis (RQ1) decrease or increase people's acceptance: *RQ2: Which factors influence laypeople's acceptance of CO_2-based jet fuel?*

By drawing on the results of RQ1 and RQ2, we analyze whether people with different levels of environmental awareness and perception of the impact of flying on the climate differ in their perception and acceptance of more climate-friendly technologies such as CO_2-based jet fuel. Environmental awareness and perception of flying were chosen as they can be indicative of broader values that influence how people evaluate sustainable (aviation) technologies (e.g., Shehawy et al., 2024; Whitmarsh et al., 2020). To furthermore formulate recommendations for communication about CO_2-based fuel, it is necessary to examine whether there are differences in informative preferences between groups with varying levels of environmental awareness and flight perception. Therefore, we ask the third research question: *RQ3: Do laypeople with different perceptions of the environment and flying differ in their perception and acceptance of CO_2-based jet fuel and in their preferences for information on the topic?*

2. Methods

The following section describes the process of data collection, including the employed study design and data preparation (2.1) as well as the description of sample characteristics (2.2) and analyses (2.3) that were used for the results described in 3.

2.1. Study design and data preparation

Before conducting a quantitative online survey, a qualitative pre-study with 12 laypeople was conducted to investigate perceptions of CO_2-based fuel and requirements and preferences in the context of being informed about this specific topic. After analyzing the interview contents by means of qualitative content analysis (Mayring, 2015), the results facilitated the design of the survey instrument. Positive and negative associations with CO_2-based jet fuel functioned as a basis for investigating public perception, while informative preferences were collected in the pre-study to be quantified in the survey.

At the beginning of the survey participants were informed about data protection measures and the purpose of the study, after which they gave their informed consent for participation. In the next step, they provided information about their age, gender, and education. After that, a series of question sets was used to measure participants' attitudes, measured (if not in the following stated otherwise) on a scale from 1 = strongly disagree to 6 = strongly agree (see Table 1 in the Supplementary Material for English translation of the German items used in the survey, item statistics, and Cronbach's α for constructs). Participants answered questions concerning their environmental awareness (Schleyer-Lindenmann et al., 2018) as it was found in previous research to impact perception and acceptance of CO_2-based fuel (Arning et al., 2023; Bergfeld et al., 2023). They furthermore indicated their flight behavior in a private and business context (measured on a rating scale from 1 = never to 6 = a few times a week for short-distance (up to 2 h), medium-distance (up to 3.5 h), and long-distance (>3.5 h) flights). As the attitude towards a behavior can impact behavioral intention (Ajzen, 1991), people's perception of flying in genera and their perception of the impact of flying on the environment (Hunecke et al., 1999) were measured. After that, participants were asked about their prior knowledge of CO_2-based jet fuel – as technology awareness was found to impact people's technology perception (Perdan et al., 2017) – and received a short text introduction to the topic (see Supplementary Material). The next part of the survey consisted of two larger sets of items for which participants indicated their (dis)agreement. The included positive and negative associations with CO_2-based fuel stemmed from the qualitative interview pre-study and were included for an explorative quantification of the results. Additionally, acceptance of CO_2-based jet fuel was assessed (Offermann-van Heek et al., 2020).

In the last part of the survey, which focused on the ways of informing or being informed about CO_2-based fuel to address *RQ3*, participants indicated how much they would like to receive information on different aspects of CO_2-based fuel (production) and on the topic in general (willingness to be informed) as well as what aspects of information on CO_2-based fuel would be of relevance to them. Finally, participants evaluated which communicators they would prefer to inform them about CO_2-based jet fuel and how they perceive the credibility of these potential communicators.

After the survey-based data collection ($n = 256$), several measures were applied to ensure data quality. The survey exclusion criteria included: early termination of the survey, as only complete data sets were used; a completion time of less than 30 % of the median completion time, to ensure sufficient engagement with instructions and item texts; inconsistent response tendencies (the same extreme response choice for oppositely worded items), as they hint at insufficient reading and comprehension of items; and outliers (cases with values differing more than three times the interquartile range from the first/third quartile), to prevent distortion of existing effects in the data.

2.2. Sample

The final data set consisted of $n = 152$ German laypeople, with 56.6 % indicating to be female, and 43.4 % to be male. The mean age was $M = 37.1$ years ($SD = 16.44$). According to the International Standard Level of Education (ISCED), most participants had a high level of education (66.4 %), followed by 31.6 % of medium level educated and a very small percentage of 2 % with a low level of education. Regarding the attitudinal factors surveyed, the sample demonstrates a high level of environmental awareness ($M = 5.01$, $SD = 0.70$, $min = 1$, $max = 6$). However, people's perception of flying is generally rather negative ($M = 2.48$, $SD = 1.06$ $min = 1$, $max = 6$), and there is a high perception that flying has a negative impact on the environment ($M = 4.67$, $SD = 1.06$ $min = 1$, $max = 6$). For flight frequency, for both the private and business context, a score was calculated based on participants' answers on the 5-point scale (min = 3, max = 18). The mean value for the collected sample for private flights was $M = 5.23$ ($SD = 1.90$), while for business flights it was $M = 3.80$ ($SD = 1.86$). Finally, respondents reported a low self-assessed knowledge of CO_2-based jet fuel ($M = 2.35$, $SD = 1.10$ $min = 1$, $max = 6$).

Table 1
Results of PCA (factor loadings) and descriptive statistics for included items measuring positive associations with CO_2-based fuel.

Item	Construct 1: *Perceived environmental benefits* (α =.89)	Construct 2: *Perceived strategic benefits* (α =.64)	Construct 3 (α =.32)	M (SD)	Difference from mid-point of scale [t_{151}] *t*	*p*
[CO_2-based fuel …]						
can help reduce everyone's carbon footprint.	0.836			4.20 (1.02)	8.52	< .001
offer the opportunity to fly in a climate-friendly way.	0.789			4.30 (1.10)	8.90	< .001
are an opportunity to reduce CO_2 emissions.	0.782			4.57 (1.03)	12.80	< .001
are a solution to combat climate change.	0.757			3.91 (1.12)	4.48	< .001
can help to improve air quality and thus bring health benefits.	0.726			4.19 (1.06)	8.04	< .001
allow me to fly with a better conscience, as I feel I am personally impacting the environment less.	0.613			4.09 (1.27)	5.76	< .001
reduce dependence on fossil energy resources (such as oil).	0.574			4.95 (0.89)	20.05	< .001
improve the image of airlines by protecting the environment.	0.559			4.50 (0.96)	12.90	< .001
are more environmentally friendly than conventional fuels, due to their production.	0.509			4.38 (1.04)	10.50	< .001
offer the opportunity to use existing infrastructure as there is no need to modify or adapt aircraft.		0.822		4.55 (1.17)	11.05	< .001
promote economic independence from imported oil from other countries.		0.642		4.60 (1.02)	13.31	< .001
can be used immediately and introduced across the board.		0.578		3.54 (1.18)	0.41	.682
make it possible to offer lower prices for flights.			0.817	2.66 (1.05)	−9.77	< .001
are a transitional solution for combating climate change because other technologies are not ready yet.			0.540	3.97 (1.10)	5.23	< .001

2.3. Data analysis

To allow inferential statistical analysis of the data, items were inverted where necessary to allow construct formation. Flight frequency was converted into a score for the private and business contexts, resulting in a minimum score of 3 for non-flyers and a maximum score of 18. To identify dimensions in different groups of items, several Principal Component Analyses (PCAs) were conducted based on the input generated on different topics in the interview pre-study. Cronbach's α (with levels of α >.6 or >.5 for two-item constructs (Taber, 2018)) was calculated for each construct. By means of a stepwise linear regression acceptance influencing factors were identified. A two-step cluster analysis (hierarchical and k-means clustering) was used to test for underlying groups in the sample for attitudes towards flying as a considered mode of transport and towards the environment. The selection of these constructs for clustering was motivated by results from previous research indicating that i) environmental awareness is a predictor for acceptance but also that ii) environmental attitudes do not necessarily translate into environmentally conscious behavior. Therefore, actual flying behavior was not included in the identification of clusters. Two-sample t-tests were used to test for differences between groups, and one-sample t-tests were used to test for trends in mean (dis)agreement (significant differences from scale mid-points). The level of significance was set at 5 %.

3. Results

The following subsections detail the results of explorative and inferential statistic analyses to identify perceptions of CO_2-based jet fuel (3.1), its acceptance predicting factors (3.2), and by identifying and comparing user groups with differing communication preference profiles (3.3).

3.1. Identification of underlying factors in public perception of CO_2-based jet fuel (RQ1)

To assess the data on CO_2-based fuel perception, principal component analysis (PCA) with Varimax rotation was performed for the two groups of items that stated positive and negative associations with CO_2-based fuel use in aviation. In the case of the positively formulated statements, three dimensions were identified. The interpretation of quality criteria for factor analysis, such as a significant Bartlett's test of Sphericity ($p < .001$) and a Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy of 0.87, allows for a subsequent analysis of the rotated component matrix. Based on factor loadings, the two constructs *perceived environmental benefits* and *perceived strategic benefits* were formed (see Table 1 for factor loadings and construct information).

The *perceived environmental benefits* construct ($M = 4.34$, $SD = 0.77$) consisted of items addressing various aspects of climate change mitigation and environmental preservation by means of utilization of CO_2-based fuel in the aviation sector. These include decreases in individual carbon footprints, fossil resources dependencies, and emissions, as well as side effects such as health benefits due to perceived heightened air quality. The highest mean approval score was attributed to the benefit of reduced fossil resource dependency ($M = 4.95$, $SD = 0.89$), while respondents least agreed that CO_2-based fuel 'are a solution to combat climate change.' ($M = 3.91$, $SD = 1.12$). Nevertheless, across the entire sample, the agreement to all the benefits grouped in this construct is significantly differing from the mid-point of the scale (see Table 1 for test-statistics), i.e., respondents on average clearly agreed upon the environmental benefits of CO_2-based fuel. *Perceived strategic benefits* ($M = 4.23$, $SD = 0.86$) entailed benefits that focus on enhancing strategic opportunities and efficiencies in the context of resource utilization. In this three-item construct, economic independence due to a lessened need for imports was most agreed upon by respondents ($M = 4.60$, $SD = 1.02$), while people least agreed to the benefit of immediate deployability of CO_2-based fuel ($M = 3.54$, $SD = 1.18$). However, in case of this specific argument, there is no clear tendency to (dis)agreement due to a lack of significant deviation from the mid-point of the scale (3.5). The internal consistency of the third factor did not allow the formation of a third construct. Interestingly, respondents clearly disagreed with the statement that it is a benefit that CO_2-based fuel could enable lower prices for passengers ($M = 2.66$, $SD = 1.05$).

In case of the negatively formulated assessments of CO_2-based fuel for aviation, PCA again revealed a three-dimension solution, with a significant Bartlett's test of Sphericity ($p < .001$) and a KMO of.73. Table 2 lists the factor loadings of the included items, six of which were excluded from further analysis due to factor loadings < .6. Two constructs were formed after checking internal consistency – *risk perception* and *economic barriers* – while the third identified group of items did not allow for the formation of a construct due to a low Cronbach's α of.53.

Based on the PCA results, the construct *risk perception* ($M = 3.54$, $SD = 0.75$) could be formed, containing items paraphrasing risks or potential harmful effects of CO_2-based fuel. For the item 'CO_2-based fuel are an unknown technology that is less trusted' ($M = 3.32$, $SD = 1.27$) there was no discernible tendency for (dis)agreement and due to increases in α it was not included in construct formation. The strongest overall agreement was identified for the risk of industry greenwashing ($M = 4.07$, $SD = 1.14$), while respondents least agreed upon potential health risks of CO_2-based fuel ($M = 2.94$, $SD = 0.94$). Three items formed the construct *perceived economic barriers* ($M = 4.12$, $SD = 0.84$), entailing perceived barriers relating to costs of CO_2-based fuel production and for passengers as end-consumers. On average, participants agreed that the production of CO_2-based fuel is costly, resulting in higher consumer costs ($M = 4.35$, $SD = 1.01$). They also rather agreed that this could potentially lead to certain consumer groups being unable to afford the increased costs ($M = 3.96$, $SD = 1.13$). The third group of items that resulted from the PCA included perceived barriers questioning the usefulness of CO_2-based fuel and the feasibility of e-fuel production in relation to energy consumption. Due to low internal consistency (α =.53), we refrained from construct formation. For the subsequent analyses, only the constructs that could be formed based on PCA will be included.

3.2. Impact of perception and other (user) factors on acceptance of CO_2-based jet fuel (RQ2)

A stepwise linear regression was conducted to investigate which (user) factors impact the acceptance of CO_2-based fuel for aviation. For the regression model with the most explanatory power, the Durbin-Watson statistic – indicating that the assumption of independent errors is met – was 1.854. The model accounted for 43.3 % explained variance (*adj.* R^2; $F_{2, 149} = 56.78$, $p < .001$). Of the group of factors that were included in the regression analysis (age, gender, education, environmental awareness, flying perception, perception of the environmental impact of flying, private and business flight frequency, self-assessed knowledge about CO_2-based fuel, as well as perception of strategic benefits and economic barriers) only two were identified as significant predictors of acceptance of CO_2-based fuel (see Table 3).

Table 2

Results of PCA (factor loadings) and descriptive statistics for included items measuring negative associations with CO_2-based fuel.

Item	Construct 1: *Risk perception* (α =.79)	Construct 2: *Perceived economic barriers* (α =.69)	Construct 3 (α =.53)	M (SD)	Difference from mid-point of scale [t_{151}] *t*	*p*
[CO_2-based fuel …]						
[…] could pose unknown risks.	0.744			3.79 (1.08)	3.29	.001
[…] could pose a risk to human health.	0.736			2.94 (0.94)	−7.31	< .001
[…] are an unknown technology that is less trusted.*	0.705			3.32 (1.27)	−1.73	.086
[…] are used by the industry to create a "green" image for itself.	0.609			4.07 (1.14)	6.10	< .001
[…] pose risks to the environment.	0.607			3.20 (0.98)	−3.73	< .001
Potentially harmful byproducts could result from the production of CO_2-based fuels.	0.558			3.69 (0.97)	2.42	.017
High costs in the production of CO_2-based fuels could increase ticket prices for air travel.		0.782		4.35 (1.01)	10.41	< .001
[…] entail high costs.		0.759		4.05 (1.08)	6.22	< .001
Due to too high costs, fewer people can afford air travel.		0.651		3.96 (1.13)	5.04	< .001
The energy consumption during production could be too high.			0.642	4.27 (1.02)	9.34	< .001
Airplanes also produce other emissions, so CO_2-based fuels are not better for the environment.			0.629	3.14 (1.00)	−4.45	< .001
There are more sensible technologies to replace petroleum as a raw material.			0.607	3.32 (1.23)	−1.85	.066
[…] pose a safety risk because existing engines have not been designed for them.	0.374			2.78 (1.05)	−8.39	< .001
[…] are not a lower-cost alternative, they are unattractive to airlines.	0.361			3.89 (1.32)	3.63	< .001
[…] are still premature and it will take time before they are mass-produced and used in the aviation sector.		0.498		4.28 (0.97)	9.99	< .001
There is not yet enough renewable energy to meet the increased electricity demand for manufacturing.		0.436		4.08 (1.33)	5.39	< .001
The long development of CO_2-based fuels delays the impact on climate change.			0.446	3.97 (0.90)	6.50	< .001
[…] do nothing to change the wasteful lifestyles of many people.			0.338	5.06 (0.95)	20.22	< .001

* Item was excluded from construct formation in favor of an increased Cronbach's α.

Table 3
Stepwise multiple linear regression model for *Acceptance of CO_2-based jet fuel.*

						95 % CI for B			
	B	*SEB*	*β*	*t*	*p*	Lower	Upper	*T*	*VIF*
(Constant)	3.385	.528		6.405	< .001	2.340	4.429		
Perceived environmental benefits	.570	.078	.502	7.321	< .001	.416	.724	.811	1.234
Risk perception	−.301	.079	−.259	−3.785	< .001	−.458	−.144	.811	1.234

Perceived environmental benefits strongly predicted acceptance with $\beta = .502$, i.e., the higher a person's perception of CO_2-based fuel utilization in aviation having a positive influence on the environment, the higher their acceptance of CO_2-based fuel. A smaller, but still significant impact factor was *risk perception*, indicating that the higher a person's risk perception towards the utilization of CO_2-based fuel, the lower their acceptance (and vice versa).

3.3. *User groups with differing information profiles (RQ3)*

A subsequent analysis was aimed at the question of whether people with differing attitudes in the context of mobility and climate change differ in their CO_2-based fuel acceptance. As a result of a two-step cluster analysis, two groups were identified based on their differing attitudes towards flying as a mode of person transport and their general environmental awareness and their awareness for the environmental impact of flying. Table 4 summarizes information on differences between the two clusters regarding demographic information, attitudes, and behavior.

There is a significant difference in terms of gender distribution between Cluster 1 ($n = 44$) and Cluster 2 ($n = 108$) as the former included more participants identifying as male while the latter consisted of more females. Cluster 2 is significantly more environmentally aware, although the mean value for environmental awareness in Cluster 1 ($M = 4.70$, $SD = 0.65$) is still significantly different from the mid-point of 3.5 ($t_{43} = 12.25$, $p < .001$, $d = 1.85$). Cluster 2 has a more negative perception of flying than Cluster 1, for which there is no clear tendency towards rejection or approval ($t_{43} = 1.86$, n. s.). The same applies to the perception of the environmental impact of flying, as there is no tendency for Cluster 1 ($t_{43} = -0.82$, n. s.), but an elevated concern for the impact of flying on the environment in Cluster 2. When it comes to behavior, the two groups significantly differ in both private and business flights throughout the last two years, although participants of both clusters flew rather little.

Interestingly, although the two clusters are significantly different in terms of the already mentioned attitudinal and behavioral aspects, they do not differ in their acceptance of CO_2-based fuel ($t_{150} = 0.0$, n. s.). The same applies to their perception of CO_2-based fuel in terms of benefits, risks, and barriers, as the differences between Clusters 1 and 2 are neither significant for perceived environmental ($t_{150} = 0.09$, n. s.) or strategic benefits ($t_{112.15} = 4.32$, n. s.) nor for risk perception ($t_{150} = 1.09$, n. s.) and perceived economic barriers ($t_{150} = 1.37$, n. s.).

However, between the two identified clusters there are several significant differences in the context of information and communication about the topic of CO_2-based jet fuel (see Fig. 1). First of all, members of Cluster 1 indicated a significantly higher level of prior knowledge CO_2-based fuel ($M = 2.73$, $SD = 1.17$) than Cluster 2 ($M = 2.20$, $SD = 1.04$, $t_{150} = 2.78$, $p = .006$, $d = .50$). At the same time, the willingness to be informed about this specific topic is higher for Cluster 2 ($M = 4.76$, $SD = 0.85$) than it is for Cluster 1 ($M = 3.95$, $SD = 0.82$, $t_{150} = -5.36$, $p < .001$, $d = -.96$).

To identify underlying dimensions in the group of information needs that people prefer to be informed about (that emerges from the pre-study), a PCA with Varimax rotation was conducted (see Table 5, Bartlett's test of Sphericity <.001, KMO =.92).

Table 4
Descriptive and inferential statistics for user characteristics for Clusters 1 and 2.

Factor	Cluster 1 ($n = 44$)	Cluster 2 ($n = 108$)	t / χ^{2}*	*p*	*d* / *V**
Age in years [*M* (*SD*)]	38.52 (17.27)	36.50 (16.13)		n. s.	
Gender [%]*			$\chi^2_1 = 10.30$	.001	.26
female	36.4	64.8			
male	63.6	35.2			
Education [%]*				n. s.	
low	0.0	2.8			
medium	40.9	27.8			
high	59.1	69.4			
Environmental awareness [*M* (*SD*)]	4.70 (0.65)	5.14 (0.67)	$t_{150} = -3.60$	< .001	−.64
Perception of flying [*M* (*SD*)]	3.74 (0.84)	1.97 (0.63)	$t_{63.24} = 12.51$	< .001	2.53
Perception of environmental impact of flying [*M* (*SD*)]	3.40 (0.83)	5.19 (0.61)	$t_{62.71} = -13.00$	< .001	−2.64
Flight frequency private [*M* (*SD*)] **	6.39 (2.07)	4.76 (1.62)	$t_{65.39} = 4.66$	< .001	.93
Flight frequency business [*M* (*SD*)] **	4.82 (2.70)	3.39 (1.16)	$t_{49.60} = 3.39$	.001	.82

* χ^2 and Cramér's *V* were calculated for nominal-scale variables.
** min = 3, max = 18.

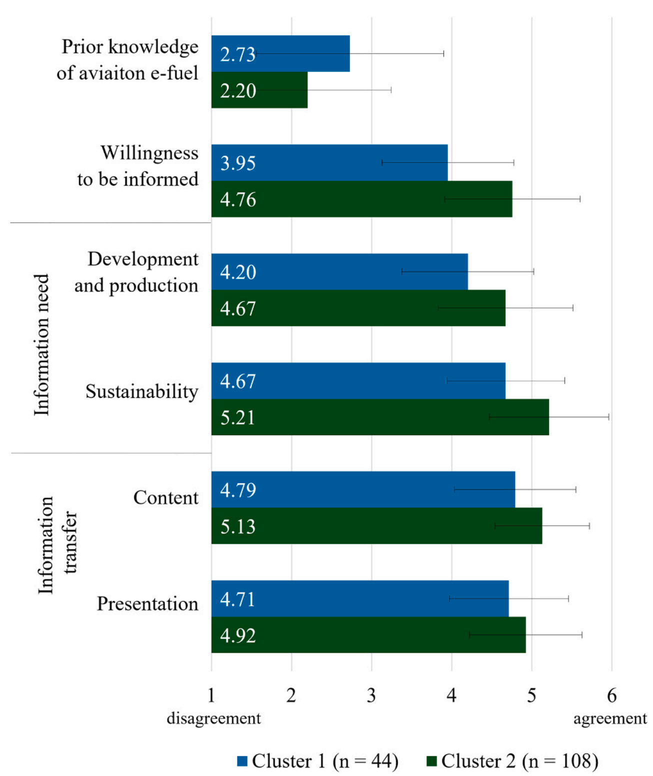

Fig. 1. Mean values of (dis)agreement for prior knowledge and willingness to know, Information needs, and Information transfer needs for Clusters 1 and 2 (whiskers indicate standard deviation).

Table 5
Results of PCA (factor loadings) and descriptive statistics for included items measuring information needs.

Item	Construct 1: *Sustainability* (α =.92)	Construct 2: *Development and production* (α =.87)	Construct 3 (α =.51)	M (SD)	Difference from mid-point of scale [t_{151}]	
					t	*p*
I would like to have detailed information about…						
the sustainability of the production.	0.842			5.12 (1.00)	19.90	< .001
the actual added value of CO_2-based fuels.	0.813			5.17 (0.97)	21.28	< .001
by-products that are emitted during production.	0.779			4.99 (0.97)	18.91	< .001
the savings in CO_2 emissions compared to conventional fuels.	0.770			5.03 (1.03)	18.43	< .001
long-term effects of CO_2-based fuels in terms of sustainability.	0.715			5.14 (0.88)	22.84	< .001
the positive effects for the climate.	0.713			5.12 (0.87)	24.36	< .001
the ecological decomposability of CO_2-based fuels.	0.708			5.06 (0.89)	21.70	< .001
the safety of CO_2-based fuels.	0.645			4.82 (1.16)	14.02	< .001
potential risks.	0.623			4.98 (0.98)	18.63	< .001
the current state of research on CO_2-based fuels.		0.547		4.75 (1.09)	14.17	< .001
the manufacturers of CO_2-based fuels.		0.798		4.31 (1.26)	7.94	< .001
production and sales costs.		0.705		4.13 (1.28)	6.08	< .001
resources (e.g. new aircraft engines, etc.) needed for CO_2-based fuels.		0.700		4.73 (1.10)	13.74	< .001
the resource extraction of CO_2-based fuels.		0.673		4.73 (1.03)	14.74	< .001
the planned market launch of CO_2-based fuels in the aviation sector.		0.672		4.61 (1.11)	12.35	< .001
the production process of CO_2-based fuels.		0.646		4.51 (1.16)	10.75	< .001
quality standards of CO_2-based fuels (e.g. ignition willingness, i.e. how easily the fuel self-ignites).		0.628		4.52 (1.17)	10.71	< .001
whether there are any financial savings on air travel for me personally.			0.816	3.97 (1.34)	4.28	< .001
the price of CO_2-based fuels.			0.550	4.72 (0.99)	15.11	< .001
where and under which conditions CO_2-based fuels are produced.		0.434		4.95 (1.02)	17.58	< .001
the energy consumption in the production of CO_2-based fuels.		0.467		4.95 (1.02)	17.58	< .001

* Item was excluded from construct formation in favor of an increased Cronbach's α.

As a result, the constructs d*evelopment and production* (e.g., information on production conditions and the state of research) and *sustainability* (e.g., information on by-products and emission savings) were built (see Table 1 in the Supplementary Material for construct information). A rather low Cronbach's α of.51 was obtained for a third factor concerning costs which is why we refrained from construct formation. For the three subgroups of information needs, significant differences were identified for the item group regarding the development and production of CO_2-based fuel for the aviation sector, as Cluster 2 on average reported a higher need for information in this regard ($M = 4.67$, $SD = 0.84$) than Cluster 1 ($M = 4.2$, $SD = 0.82$, $t_{150} = -3.16$, $p = .002$, $d = -.57$). Same applies to sustainability information, as Cluster 2 ($M = 5.21$, $SD = 0.74$) is again more interested in being informed in this context than Cluster 1 ($M = 4.67$, $SD = 0.73$, $t_{150} = -4.08$, $p < .001$, $d = -.73$).

Furthermore, respondents were asked what they considered to be good and effective information communication. An additional PCA (see Table 6 for construct information) for these items (Bartlett's test of Sphericity <.001, KMO =.85) revealed two underlying dimensions: *content* (i.e., facets referring to the contents of provided information, e.g., detailedness and expert opinions) and *presentation* (i.e., facets referring to the visual representation of information, e.g., simplified representation and media diversity (text, figures, animations, etc.)).

Notably, Cluster 2 ($M = 5.13$, $SD = 0.59$) considers the presentation of information content to be more relevant for good and effective communication of information on the topic of CO_2-based fuel than Cluster 1 ($M = 4.79$, $SD = 0.76$, $t_{150} = -2.94$, $p = .004$, $d = -.53$). In contrast, there is no difference between the two groups for the perceived relevance of visual presentation ($t_{150} = -1.65$, n. s.). Both groups rated this aspect of information presentation as rather important.

Finally, to answer the question of which bodies should inform the public about CO_2-based fuel, it is helpful to consider channel preference and perceived credibility (see Fig. 2). Manufacturers or industry and companies or airlines were rather not preferred and deemed as rather not credible by Cluster 2, while Cluster 1 perceived manufacturers of CO_2-based fuel rather not credible as well but did not exhibit a clear preference for or against these instances as communicators, as would be demonstrated by significant differences from the midpoint of the scale (3.5). However, on average, Cluster 1 reported a significantly higher preference to be informed by companies or airlines ($M = 3.75$, $SD = 1.12$) than Cluster 2 ($M = 3.19$, $SD = 1.38$, $t_{150} = 2.36$, $p = .019$, $d = .42$). For private television or radio stations moderate results indicate there is no clear trend evident in the data with the exception of perceived credibility by Cluster 2 (which significantly deviates from 3.5). In

Table 6
Results of PCA (factor loadings) and descriptive statistics for included items measuring preferences for information transfer.

Item	Construct 1: *Content* (α =.80)	Construct 2: *Presentation* (α =.80)	*M (SD)*	Difference from mid-point of scale [t_{151}]	
				t	*p*
In your opinion, what requirements must good and effective information delivery meet?					
objectivity and neutrality	0.748		5.39 (0.77)	30.14	< .001
transparency	0.742		5.28 (0.91)	24.13	< .001
seriousness	0.715		5.16 (0.85)	24.15	< .001
expert opinions	0.672		4.74 (1.10)	13.93	< .001
detailedness	0.616		4.36 (1.02)	10.42	< .001
independence (from economic interests)	0.557		5.26 (0.91)	23.85	< .001
understandability	0.538		5.45 (0.74)	32.27	< .001
clear presentation		0.806	5.09 (0.85)	23.13	< .001
visual demonstration		0.793	4.72 (1.01)	14.92	< .001
media diversity (texts, graphics, animations, etc.)		0.718	4.50 (1.10)	11.23	< .001
simplified representation		0.658	4.57 (1.06)	12.41	< .001

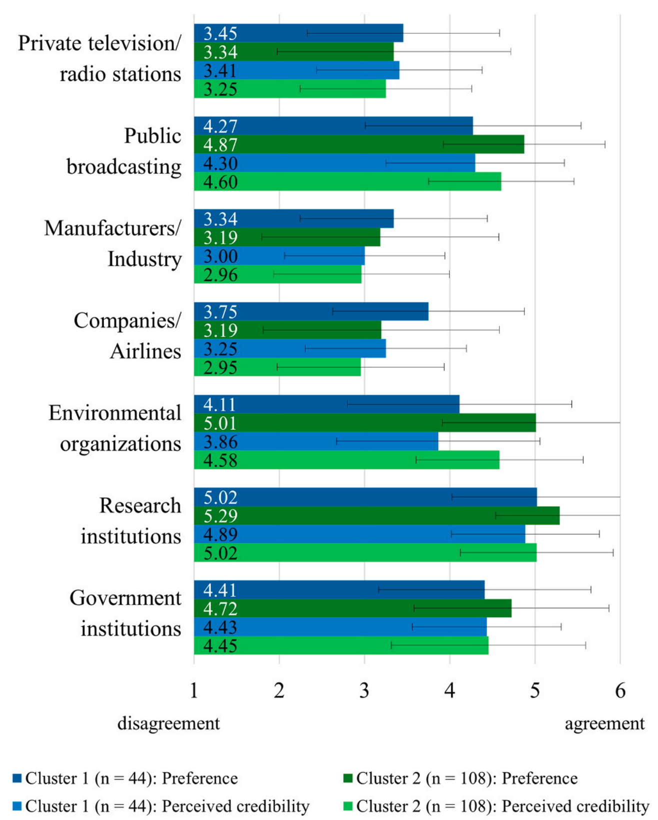

Fig. 2. Mean values of (dis)agreement for communicator preference and perceived credibility of communicators for Clusters 1 and 2 (whiskers indicate standard deviation).

contrast to that, public broadcasting is on average more positively perceived. In this case, the preference for this communicator ($M = 4.87$, $SD = 0.95$) by Cluster 2 is significantly higher than that of Cluster 1 ($M = 4.27$, $SD = 1.26$; $t_{63.62} = -2.83$, $p = .006$, $d = -.57$), while there is no significant difference in terms of perceived credibility of public broadcasting ($t_{150} = -1.88$, n. s.). Research and government institutions were rather preferred and rather perceived to be credible communicators, however, there are no significant differences between Clusters 1 and 2 for preference (research institutions: $t_{63.61} = -1.58$, n. s.; government institutions: $t_{150} = -1.49$, n. s.) or perceived credibility (research institutions: $t_{150} = -0.83$, n. s.; government institutions: $t_{150} = -0.11$, n. s.). Finally, for the case of environmental organizations, Clusters 1 and 2 differ in their perception, as Cluster 2 has both a higher preference to be informed by these organizations about CO_2-based fuel ($M = 5.01$, $SD = 1.10$) than Cluster 1 ($M = 4.11$, $SD = 1.32$, $t_{68.64} = -3.99$, $p < .001$, $d = -.77$) and perceives these actors to be of more credibility ($M = 4.58$, $SD = 0.98$) than members of Cluster 2 do ($M = 3.86$, $SD = 1.19$, $t_{67.71} = -3.55$, $p = .001$, $d = -.69$).

4. Discussion

4.1. *Identified factors in laypeople's perception of CO_2-based jet fuel*

After identifying acceptance relevant factors from the broader field of positive and negative associations observed in a qualitative interview study, principal component analysis (PCA) revealed that laypersons predominantly perceived benefits associated with various facets of sustainability. This supports previous findings that perceptions of carbon dioxide removal are associated with sustainability (Haverkämper et al., 2023), although concerns about sustainability issues were also identified (Cox et al., 2020). However, there is a noticeable divergence in agreement as to whether CO_2-based jet fuel is a comprehensive solution to mitigating climate change. This implies that while respondents recognize environmental benefits, they may not view CO_2-based fuel as a definitive solution to address climate change. Similarly, perceived strategic benefits received a level of agreement comparable to sustainability benefits, particularly concerning dependencies on imports and immediate applicability within existing infrastructure. Nevertheless, the immediate deployability of CO_2-based fuel was assessed moderately, indicating potential reservations or uncertainties regarding the feasibility and preparedness of this technology. This observation aligns with the relatively high agreement regarding the perception of prematurity as expressed as a perceived barrier. Investigating the associations of laypeople contributing to this perception in more detail could inform strategies aimed at addressing barriers to adoption and deployment, such as technological readiness and infrastructure development. In this context, community perception of sustainable infrastructure development is an essential aspect to be considered (Sovacool et al., 2024).

Notably, concerning the identified cluster of risk perceptions, the most strongly agreed-upon drawback is the risk of industry greenwashing. This skepticism, in line with the lesser agreement regarding the notion of CO_2-based jet fuel as a solution to climate change, suggests that although there is a rather high level of acceptance toward the product, laypeople also harbor doubts regarding its overall suitability. Overall, the construct of risk perception and related threats are not prominently elevated, suggesting a low likelihood of rejection based on fears regarding the potential dangers posed by CO_2-based jet fuel. This finding resonates with findings on a low risk perception in connection to perceived harmfulness of CO_2-based fuel (Engelmann et al., 2020).

4.2. *Impacting factors on laypeople's acceptance of CO_2-based jet fuel*

Regression analysis was used to investigate the factors that influence perceptions and attitudes towards CO_2-based jet fuel in aviation. Surprisingly, only two of the predictors included had a significant impact on the acceptance of CO_2-based jet fuel, explaining a moderate level of variance. Perceived environmental benefits positively predict acceptance, while risk perception has a negative influence. This is consistent with previous research on CO_2-based fuel acceptance (Arning et al., 2023). However, unlike Arning et al. (2023), this study did not find any user-related factors that predict acceptance. They found that environmental awareness and the construct of flight shame impacted a person's acceptance of CO_2-based jet fuels, which could not be replicated in this study (Arning et al., 2023). Nevertheless, these results imply that communication efforts related to risk could be useful in providing public information on this topic. Although risk perception was not elevated, informing laypeople about the factual risks of fuel alternatives (e.g., in comparison to conventionally used kerosene) or sustainable developments in general, enables them to make informed decisions. This is particularly relevant when booking a flight or making decisions related to sustainable developments in general, such as public participation and voting. The strength of this study in terms of acceptance analysis – compared for example to the work by Arning et al. (2023) or Linzenich et al. (2023) – lies in the multi-method supported approach, which was used to scrutinize the diversity of perceived benefits and barriers in the interviews and subsequently test their acceptance impact. The inclusion of the numerous identified factors of perception enables a broad view of CO_2-based fuel as a new type of fuel for aviation. Furthermore, the identification of two clusters allowed for an in-depth analysis of communicative needs.

4.3. Perceptions of environment and flying affect the acceptance of CO_2-based jet fuel

After identifying two distinct clusters of people with differing levels of flying perception and environmental awareness, we observed the absence of differences in acceptance and perception of CO_2-based jet fuel, which is intriguing given that environmental awareness and knowledge have been identified in other studies as a predictor of technology acceptance and behavioral intention in the climate context (Ferreira et al., 2023; Neves et al., 2025).

Although it may be less surprising concerning production and development, when it comes to sustainability, one might have expected individuals with higher awareness of the impacts of flying on climate change and a greater environmental consciousness to perceive the use of CO_2-based jet fuel as more advantageous. However, perhaps this is also due to the fact that although the perception is generally positive, if one looks at the average values for the benefit perception and the relatively high acceptance of CO_2-based fuel, there is also the barrier perception that people's behavior, their wasteful lifestyle, will not change as a result of this technology.

Another aspect to be considered is the potential impact of other factors not included in this study that are vital for explaining acceptance could shed light on this missing link. For example, social norms were found to impact the intention to reduce flight behavior (Hansmann and Binder, 2021) and should therefore be included in future studies. Neves et al. (2025) identified habit as a significant predictor for behavioral intention regarding the use of sustainable technologies. However, CO_2-based fuel is a novel technology that does not yet offer the option of habit formation. Regarding a potential habituation of aviation as the technology context in question: the number of flights prior to the study was relatively low for both clusters. Taking this and the other aspects mentioned into account, the circumstance that flying is an activity that many people do less frequently than other modes of transport, and whose environmental impact could therefore be classified as less relevant in individual cases (although in one cluster the perception of environmental impact was quite high), could explain the lack of acceptance here due to the low number of flights in the sample.

4.4. Environment/flying perceptions impact information needs on CO_2-based jet fuel

The initial surprising finding regarding the differences between the clusters is related to the measured levels of prior knowledge and interest. Cluster 1, consisting of individuals with higher flight activity and more positive evaluations of flying in general, but with lower perceptions of the environmental impact of flying and environmental consciousness, indicate having more knowledge about CO_2-based jet fuels. The assessment may be based on a level of familiarity with flying or on actual higher levels of knowledge (not verifiable by self-report measures) compared to Cluster 2. Cluster 2 expressed a higher willingness to be informed, which is consistent with this. It would be useful to understand why no differences were found between the clusters in their assessment of benefits, barriers, and risks if knowledge actually differed between groups. However, prior knowledge was also not identified as a significant predictor of acceptance, as measured in other studies (Baral, 2018).

Individuals with higher environmental awareness (also in the context of aviation) are more interested in information. It is noteworthy that some dimensions identified in RQ1 are reflected in the information needs, such as sustainability. Although no significant differences were found between the clusters in their perception of benefits, risks, and barriers, they expressed a desire to be informed about these aspects. The study also revealed a difference in the 'how' aspect of information preferences, specifically in the characteristics of the content, such as its seriousness and transparency. The results suggest that information needs are more closely related to this dimension, while requirements for visual presentation of content do not differ significantly between Clusters 1 and 2. This indicates that content is prioritized over presentation, which appears to operate on a more general level.

Finally, when it comes to informing entities, official institutions such as environmental, research, and governmental bodies are preferred. The perception that entities representing commercial interests (such as industry and companies like airlines) are less credible is in line with previous findings where lower levels of trust were observed for entities such as industry or companies. These results highlight the importance of tailoring information strategies to specific user groups. When communicating public information about innovative products such as CO_2-based jet fuel it is important to consider both the information content and the communicator as the sender of information. It is important to note that there is no universal solution that fits all situations or countries–as this study focused solely on German laypeople and other cultural background may go hand in hand with different or opposing communicative patterns and preferences. However, social groups can be categorized based on their personality traits, such as environmental awareness and attitude towards flying. These groups do not necessarily have to differ in their perception and acceptance, but they do have different needs in terms of how they are informed about sustainable technologies. Communicators involved in the production and roll-out of sustainable propulsion technologies and products such as CO_2-based jet fuel can draw on these results for their public communication. There is a need for an awareness of the differences in communicator preference and perceived credibility that should encourage, for example, airlines to carefully design their public communication strategies. Collaborating with trusted and neutral sources of information while being transparent about motives and including information in which consumers have an increased interest can be one option for user-centered information provision. Finally, one should take into consideration that technologies undergo phases of innovation acceptance by society (Rogers, 1995) and that therefore, iterative revisiting of potentially changing public communication and information needs by communicators is crucial.

5. Conclusion

CO_2-based fuel offers the opportunity for an emission heavy sector such as aviation to operate in a more climate-friendly way. Analyzing public perception and acceptance of novel propulsion technologies such as CO_2-based jet fuel helps understanding potential barriers but also factors facilitating the implementation of the fuel. In this study we achieved a holistic view on the perception of the fuel and how they impact acceptance while also investigating distinct user profiles regarding information needs. The findings underline that the public should not be treated as one homogenous stakeholder group but that there are societal segments with differing levels of preexisting knowledge and acceptance levels as well as information requirements. Based on these results we recommend the formation of user-targeted information strategies that allow informing the public according to the identified groups' needs.

CRediT authorship contribution statement

Engelmann Linda: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Offermann Julia:** Writing – review & editing, Writing – original draft, Formal analysis. **Ziefle Martina:** Writing – review & editing, Project administration, Funding acquisition.

Funding

The work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy—Cluster of Excellence 2186 "The Fuel Science Center" ID: 390919832 as well as by the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 838077. Linda Engelmann would furthermore like to thank the "DAC-TALES" project funded by the German Federal Ministry of Education and Research (BMBF) for support (01LS2106A). Open Access funding was covered by the DEAL Agreement.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Kind thanks to Isabelle Wanders for support regarding data collection.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.egyr.2025.05.008.

Data availability

Data will be made available on request.

References

Abbas, Z., Mezher, T., Abu-Zahra, M.R.M., 2013. CO2 purification. Part I: Purification requirement review and the selection of impurities deep removal technologies. Int. J. Greenh. Gas. Control 16, 324–334. https://doi.org/10.1016/j.ijggc.2013.01.053.

Ajzen, I., 1991. The theory of planned behavior. Organ. Behav. Hum. Decis. Process 50, 179–211.

Al-Mamoori, A., Krishnamurthy, A., Rownaghi, A.A., Rezaei, F., 2017. Carbon capture and utilization update. Energy Technol. 5, 834–849. https://doi.org/10.1002/ente.201600747.

Arning, K., Engelmann, L., Ziefle, M., 2023. Ready to fly? Comparing acceptance and behavioral usage intentions of CO2-based aviation fuels in four European countries. Front. Energy Res. 11.

Baral, N., 2018. What socio-demographic characteristics predict knowledge of biofuels. Energy Policy 122, 369–376. https://doi.org/10.1016/j.enpol.2018.07.038.

Barke, A., Bley, T., Thies, C., Weckenborg, C., Spengler, T.S., 2022. Are sustainable aviation fuels a viable option for decarbonizing air transport in Europe? An environmental and economic sustainability assessment. Appl. Sci. 12, 597. https://doi.org/10.3390/app12020597.

Bergfeld, M., Obersteller, D., Nguyen, D.M., Anderson, J.E., Nobis, C., 2023. Real-world insights into user acceptance of e-fuels for passenger vehicles in Germany. Transp. Res. Procedia, TRA Lisbon 2022 Conference Proceedings Transport Research Arena (TRA Lisbon 2022),14th-17th November 2022, Lisboa, Portugal 72, 1303–1310. https://doi.org/10.1016/j.trpro.2023.11.591.

Boudet, H.S., 2019. Public perceptions of and responses to new energy technologies. Nat. Energy 4, 446–455. https://doi.org/10.1038/s41560-019-0399-x.

Burstein, P., 2003. The impact of public opinion on public policy: a review and an agenda. Polit. Res. Q. 56, 29–40. https://doi.org/10.1177/106591290305600103.

Cox, E., Spence, E., Pidgeon, N., 2020. Public perceptions of carbon dioxide removal in the United States and the United Kingdom. Nat. Clim. Change 10, 744–749. https://doi.org/10.1038/s41558-020-0823-z.

D'Amato, A., Giaccherini, M., Zoli, M., 2019. The role of information sources and providers in shaping green behaviors. Evidence from Europe. Ecol. Econ. 164, 106292. https://doi.org/10.1016/j.ecolecon.2019.04.004.

Desport, L., Selosse, S., 2022. Perspectives of CO2 utilization as a negative emission technology. Sustain. Energy Technol. Assess. 53, 102623. https://doi.org/10.1016/j.seta.2022.102623.

Dethloff, C., 2004. Akzeptanz und Nicht-Akzeptanz von technischen Produktinnovationen. Pabst Science Publ.

Dieterich, V., Buttler, A., Hanel, A., Spliethoff, H., Fendt, S., 2020. Power-to-liquid via synthesis of methanol, DME or Fischer–Tropsch-fuels: a review. Energy Environ. Sci. 13, 3207–3252. https://doi.org/10.1039/D0EE01187H.

ElHaffar, G., Durif, F., Dubé, L., 2020. Towards closing the attitude-intention-behavior gap in green consumption: a narrative review of the literature and an overview of future research directions. J. Clean. Prod. 275, 122556. https://doi.org/10.1016/j.jclepro.2020.122556.

Engelmann, L., Arning, K., Linzenich, A., Ziefle, M., 2020. Risk assessment regarding perceived toxicity and acceptance of carbon dioxide-based fuel by laypeople for its use in road traffic and aviation. Front. Energy Res. 8. https://doi.org/10.3389/fenrg.2020.579814.

Engelmann, L., Arning, K., Ziefle, M., 2024. One step closer: Laypeople's perception of production steps for manufacturing CO2-based jet fuel. Energy Sustain. Soc. 14, 9. https://doi.org/10.1186/s13705-024-00441-8.

Eurostat, 2025. Air passenger transport statistics [WWW Document]. URL ⟨https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Air_passenger_transport_statistics⟩ (Accessed 2.3.25).

Ferreira, L., Oliveira, T., Neves, C., 2023. Consumer's intention to use and recommend smart home technologies: the role of environmental awareness. Energy 263, 125814. https://doi.org/10.1016/j.energy.2022.125814.

Galimova, T., Ram, M., Bogdanov, D., Fasihi, M., Khalili, S., Gulagi, A., Karjunen, H., Mensah, T.N.O., Breyer, C., 2022. Global demand analysis for carbon dioxide as raw material from key industrial sources and direct air capture to produce renewable electricity-based fuels and chemicals. J. Clean. Prod. 373, 133920. https://doi.org/10.1016/j.jclepro.2022.133920.

Goodarzi, S., Masini, A., Aflaki, S., Fahimnia, B., 2021. Right information at the right time: reevaluating the attitude–behavior gap in environmental technology adoption. Int. J. Prod. Econ. 242, 108278. https://doi.org/10.1016/j.ijpe.2021.108278.

Hansmann, R., Binder, C.R., 2021. Reducing personal air-travel: restrictions, options and the role of justifications. Transp. Res. Part Transp. Environ. 96, 102859. https://doi.org/10.1016/j.trd.2021.102859.

Hasan, M.M.F., First, E.L., Boukouvala, F., Floudas, C.A., 2015. A multi-scale framework for CO2 capture, utilization, and sequestration: CCUS and CCU. Comput. Chem. Eng., Special Issue: Selected papers from the 8th International Symposium on the Foundations of Computer-Aided Process Design (FOCAPD 2014), July 13-17, 2014, Cle Elum, Washington, USA 81, 2–21. https://doi.org/10.1016/j.compchemeng.2015.04.034.

Haverkämper, I., Wilkowska, W., Ziefle, M., 2023. What makes people accept carbon capture and utilization products? Exploring requirements of use in the German population. Front. Energy Res. 11. https://doi.org/10.3389/fenrg.2023.1248555.

Huijts, N.M.A., Molin, E.J.E., Steg, L., 2012. Psychological factors influencing sustainable energy technology acceptance: a review-based comprehensive framework. Renew. Sustain. Energy Rev. 16, 525–531. https://doi.org/10.1016/j.rser.2011.08.018.

Hunecke, M., Blöbaum, A., Matthies, E., Höger, R., 1999. Problemwahrnehmung spezifisch. Zs. Soz. Item Skalen ZIS. https://doi.org/10.6102/ZIS177.

IEA, 2022. Aviation – Analysis. ⟨https://www.iea.org/reports/aviation⟩.

Jones, et al., 2015. Investigating public perceptions of carbon dioxide utilisation (CDU) technology: a mixed methods study. Faraday Discuss. 183, 327–347.

Küng, L., Aeschlimann, S., Charalambous, C., McIlwaine, F., Young, J., Shannon, N., Strassel, K., Maesano, Nichole, Kahsar, C., Pike, R., Spek, D., van der, M., Garcia, S., 2023. A roadmap for achieving scalable, safe, and low-cost direct air carbon capture and storage. Energy Environ. Sci. 16, 4280–4304. https://doi.org/10.1039/D3EE01008B.

Linzenich, A., Bongartz, D., Arning, K., Ziefle, M., 2023. What's in my fuel tank? Insights into beliefs and preferences for e-fuels and biofuels. Energy Sustain. Soc. 13, 35. https://doi.org/10.1186/s13705-023-00412-5.

Liu, W., Wang, C., Mol, A.P.J., 2013. Rural public acceptance of renewable energy deployment: the case of Shandong in China. Appl. Energy, Spec. Issue Adv. Sustain. biofuel Prod. Use - XIX Int. Symp. . Alcohol Fuels - ISAF 102, 1187–1196. https://doi.org/10.1016/j.apenergy.2012.06.057.

Lutzke, L., Árvai, J., 2021. Consumer acceptance of products from carbon capture and utilization. Clim. Change 166, 15. https://doi.org/10.1007/s10584-021-03110-3.

Mayring, P., 2015. Qualitative Inhaltsanalyse: Grundlagen und Techniken. Beltz.

McDonald, S., Oates, C.J., Thyne, M., Timmis, A.J., Carlile, C., 2015. Flying in the face of environmental concern: why green consumers continue to fly. J. Mark. Manag 31, 1503–1528. https://doi.org/10.1080/0267257X.2015.1059352.

Neves, C., Oliveira, T., Cruz-Jesus, F., Venkatesh, V., 2025. Extending the unified theory of acceptance and use of technology for sustainable technologies context. Int. J. Inf. Manag 80, 102838. https://doi.org/10.1016/j.ijinfomgt.2024.102838.

Nocito, F., Dibenedetto, A., 2020. Atmospheric CO2 mitigation technologies: carbon capture utilization and storage. Curr. Opin. Green. Sustain. Chem., N. Synth. Methods ● Sel. Pap. 4th Green. SustaiN. Chem. Conf. 21, 34–43. https://doi.org/10.1016/j.cogsc.2019.10.002.

Offermann-van Heek, J., Arning, K., Sternberg, A., Bardow, A., Ziefle, M., 2020. Assessing public acceptance of the CO2-derived fuel life cycle. does information make the difference? Energy Policy 143. https://doi.org/10.1016/j.enpol.2020.111586.

Oltra, C., Dütschke, E., Preuß, S., Gonçalves, L., Germán, S., 2022. What influences public attitudes and acceptance of CCUS technologies on the national and regional level? Results from a survey study in France and Spain. https://doi.org/10.2139/ssrn.4272128.

Oswald, L., Ernst, A., 2021. Flying in the Face of Climate Change: quantitative psychological approach examining the social drivers of individual air travel. J. Sustain. Tour. 29, 68–86. https://doi.org/10.1080/09669582.2020.1812616.

Ozkan, M., Narappa, A.B., Namboodiri, T., Chai, Y., Babu, M., Jennings, J.S.E., Gao, Y., Tasneem, S., Lam, J., Talluri, K.R., Shang, R., Ozkan, C.S., Watkins, J.M., 2024. Forging a sustainable sky: unveiling the pillars of aviation e-fuel production for carbon emission circularity. iScience, 109154. https://doi.org/10.1016/j.isci.2024.109154.

Perdan, S., Jones, C.R., Azapagic, A., 2017. Public awareness and acceptance of carbon capture and utilisation in the UK. Sustain. Prod. Consum 10, 74–84. https://doi.org/10.1016/j.spc.2017.01.001.

Raman, R., Gunasekar, S., Dávid, L.D., Rahmat, A.F., Nedungadi, P., 2024. Aligning sustainable aviation fuel research with sustainable development goals: trends and thematic analysis. Energy Rep. 12, 2642–2652. https://doi.org/10.1016/j.egyr.2024.08.076.

Rogers, E.M., 1995. Diffusion of Innovations, 4th ed. Free Press, New York.

Rojas-Michaga, M.F., Michailos, S., Cardozo, E., Akram, M., Hughes, K.J., Ingham, D., Pourkashanian, M., 2023. Sustainable aviation fuel (SAF) production through power-to-liquid (PtL): a combined techno-economic and life cycle assessment. Energy Convers. Manag 292, 117427. https://doi.org/10.1016/j.enconman.2023.117427.

Schleyer-Lindenmann, A., Ittner, H., Dauvier, B., Piolat, M., 2018. Die NEP-Skala – hinter den (deutschen) Kulissen des Umweltbewusstseins. Diagnostica.

Schmidt, P., Batteiger, V., Roth, A., Weindorf, W., Raksha, T., 2018. Power-to-liquids as renewable fuel option for aviation: a review. Chem. Ing. Tech. 90, 127–140. https://doi.org/10.1002/cite.201700129.

Shehawy, Y.M., Khan, S.M.F.A., Madkhali, H., 2024. An integrated SEM-ESG framework for understanding consumer's green technology adoption behavior. J. Knowl. Econ. https://doi.org/10.1007/s13132-024-02231-1.

Skov, I.R., Schneider, N., 2022. Incentive structures for power-to-X and e-fuel pathways for transport in EU and member states. Energy Policy 168, 113121. https://doi.org/10.1016/j.enpol.2022.113121.

Sovacool, B.K., AbdulRafiu, A., Hudson, M., McManus, M., Korre, A., Marr, I., Howard, C., Maroto-Valer, M.M., 2024. Beyond the factory: ten interdisciplinary lessons for industrial decarbonisation practice and policy. Energy Rep. 11, 5935–5946. https://doi.org/10.1016/j.egyr.2024.05.048.

Taber, K.S., 2018. The use of Cronbach's Alpha when developing and reporting research instruments in science education. Res. Sci. Educ. 48, 1273–1296. https://doi.org/10.1007/s11165-016-9602-2.

Thonemann, N., Pizzol, M., 2019. Consequential life cycle assessment of carbon capture and utilization technologies within the chemical industry. Energy Environ. Sci. 12, 2253–2263. https://doi.org/10.1039/C9EE00914K.

Tosun, J., 2018. The behaviour of suppliers and consumers in mandated markets: the introduction of the ethanol–petrol blend E10 in Germany. J. Environ. Policy Plan 20, 1–15. https://doi.org/10.1080/1523908X.2017.1299624.

Whitmarsh, L., Capstick, S., Moore, I., Köhler, J., Le Quéré, C., 2020. Use of aviation by climate change researchers: structural influences, personal attitudes, and information provision. Glob. Environ. Change 65, 102184. https://doi.org/10.1016/j.gloenvcha.2020.102184.

Wüstenhagen, R., Wolsink, M., Bürer, M.J., 2007. Social acceptance of renewable energy innovation: an introduction to the concept. Energy Policy 35, 2683–2691.