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Ready to fly? Comparing acceptance and behavioral usage intentions of CO_2-based aviation fuels in four European countries

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Significantly increased global greenhouse gas emissions from aviation make the decarbonization of the aviation sector an urgent demand to combat climate change. One technical approach is the usage of Carbon Capture and Utilization technologies (CCU) to re-use CO_2 as raw material and to produce CO_2-based aviation fuels. As the social readiness is an essential component for a successful roll-out, this study investigates acceptance and behavioral usage intentions regarding CO_2-based aviation fuels. We applied an empirical quantitative online questionnaire in four European countries (Spain, Norway, Netherlands, and Germany, N = 2,187). To get a comprehensive overview of the factors that predict social readiness, data on relevant impact factors were collected, including sociodemographic factors, awareness, attitudinal factors (innovation cautiousness, environmental awareness, flight shame), flight behavior as well as evaluations in terms of benefit and risk perceptions of CO_2-based fuels. Employing hierarchical regression analyses we identified the impact of individual factors and fuel-related perceptions on the acceptance of and the willingness to use CO_2-based aviation fuels. For the prediction of CO_2-based fuel acceptance, benefit perceptions were the strongest predictor, followed by environmental awareness, risk perceptions, interest, and flight shame. For the behavioral intention to fly with CO_2-based fuels, benefit perceptions showed the strongest impact, followed by environmental awareness, interest, and risk perceptions about technical quality and -maturity as well as health- and environmental risks. This was valid for all four European countries under study, even though there were also national differences: Norwegian respondents showed the lowest interest in and knowledge of CO_2-based aviation fuels and the lowest acceptance. Spanish respondents reported the highest acceptance, while acceptance scores of German and Dutch residents ranged in between. Overall, the findings provide a pan-European insight into the social readiness for CO_2-based aviation fuels and its determinants, providing targeted information on public adoption conditions and requirements for Carbon Capture and Utilization technology developers and the aviation industry.

KEYWORDS

CO_2-based fuels, Carbon Capture and Utilization (CCU), regression analyses, social readiness, acceptance, aviation, perceptions, willingness to fly

1 Introduction

Combating climate change is one of the greatest current global challenges. One contributor to climate change is the sharp increase in CO_2 emissions into the atmosphere since industrialization (Dong et al., 2019). Most countries have set ambitious targets to reduce CO_2 emissions through reduced use and combustion of fossil resources and more efficient processes, production routes, and products (UNFCCC, 2015). However, current global CO_2 emissions show that these targets are missed in most sectors and that CO_2 emissions continue to rise globally (IPCC, 2022). As the transport sector is the most dependent on fossil fuels, it accounted for 37% of global CO_2 emissions in 2021 (IEA, 2022). Global greenhouse gas emissions from aviation have also steadily increased through 2019 to 915 million tons of CO_2 per year (ATAG, 2022). After the pandemic-related decline in aviation, it is expected that there will be continued growth in emissions from this sector (IEA, 2022).

One approach to defossilize the transport sector is the development of CO_2-based fuels, which are based on Carbon Capture and Utilization (CCU) technologies. CCU uses CO_2 captured from ambient air or industrial emissions as a raw material to produce fuels (Markewitz et al., 2012). CO_2-based fuels exhibit high energy density and, if produced from renewable energy sources, can be produced in an almost carbon-neutral manner. In addition, they can contribute to a reduction in pollutants such as NOx and particulate matter (Deutz et al., 2018).

In addition to the significant challenges in developing sustainable production pathways and economic conditions (Bann et al., 2017), a critical issue is the societal perception and acceptance of CO_2-based aviation fuels. Novel and more sustainable energy systems, technologies, and products do not always meet with favorable public reaction and acceptance. Occasionally, they elicit negative perceptions, rejective attitudes, protests, or boycotts that can hinder or even stop these developments and projects or market penetration, e.g., low acceptance and protests against wind parks (Devine-Wright and Batel, 2017), biofuel boycott in Germany (Tosun, 2018), protests against the implementation of CCS in the Netherlands or Germany (Orange Seigo et al., 2014), risk perceptions concerning the production infrastructure of CO_2-based aviation fuels (Simons et al., 2021). In parallel with the development of more sustainable fuel alternatives for the aviation sector based on CCU technology application, it is important to understand the public perception and willingness to fly with CO_2-based aviation fuel. This study empirically investigates public readiness in terms of acceptance and willingness to fly regarding CO_2-based aviation fuels in four European countries.

2 Carbon Capture and Utilization and CO_2-based fuels in aviation

CCU is a technological approach by which CO_2 is used as a feedstock to produce carbon-based materials and products such as chemicals, building materials, polymers, or fuels (Kätelhön et al., 2019; Mustafa et al., 2020; von der Assen and Bardow, 2014). CCU involves the capture, transport, and subsequent use of carbon compounds, usually in the form of carbon dioxide (CO_2) or carbon monoxide (CO). Thereby, the carbon is fed into at least one further usage cycle. To achieve fully renewable energy systems, CCU is considered an important building block. This holds especially in areas such as aviation, which have little or no electrification potential and will continue to require high-energy-density fuels. Even though alternative energy sources such as hydrogen or electricity are discussed in addition to optimized combustion engines, these are not (yet) suitable for use in the long-haul sector, which accounts for the largest share of CO_2 emissions (Larsson et al., 2019). CO_2-based aviation fuels have the advantage of being immediately deployable as part of the existing infrastructure. Considering the long lifetime and therefore lengthy renewal period of the flight infrastructure, this can be considered an advantage of the replacement of conventional fuels by CO_2-based aviation fuel (Scheelhaase et al., 2019). However, large amounts of water and renewable energy will be needed to produce CO_2-based aviation fuels (Gössling and Lyle, 2021). Thus, sufficient renewable energy must be available for sustainable and CO_2-neutral production of CO_2-based fuels (Wich et al., 2020) and potential water source conflicts (e.g., in competition with agriculture) need to be anticipated in implementation planning (Cabrera and de Sousa, 2022). Furthermore, the implementation of CCU technology requires the construction of new production facilities and the adaptation of existing facilities. If these investments in industrial infrastructure are made and the requirements of an energy system based on renewable energy are met, it is estimated that by producing CO_2-based fuels CO_2 emissions can be reduced by 34% compared to conventionally produced fossil fuels (Zakkour et al., 2018). Furthermore, estimates are that the use of sustainable aviation fuel can result in pollutant reduction, e.g., soot (Gaspar and Sousa, 2016), particulate matter (Durdina et al., 2012). Despite numerous advantages of replacing conventional fuels with alternatives such as CO_2-based fuels, there are several hurdles that complicate this process, e.g., production cost, as the production of CO_2-based fuels is currently more expensive than conventional fossil fuels (Do et al., 2022), limited availability of the required amount of resources, lack of support from both national and international legislature, as well as questions concerning scalability and economic feasibility arising from it (Cabrera and de Sousa, 2022).

The current study assumes a CCU process that involves CO_2 capture from industrial exhaust streams. There are several potential methods for capturing CO_2 from industrial waste gas streams, such as membrane adsorption, cryogenic capture, or the use of physical solvents (Mustafa et al., 2020). Depending on the impurity of the waste gas stream, it may be necessary to purify the captured CO_2 before further use as a production feedstock. The choice of purification process depends on the nature of the impurities in the off-gas stream (Pires da Mata Costa et al., 2021). After purification and treatment, the CO_2 must be transported to the CCU production plant *via* pipelines, trucks, and ships, if it is not used directly on-site (Pieri et al., 2018). In a final step, the CO_2 is converted into CO_2-based fuels. Various processes can be used in the production of CO_2-based fuels, the most prominent routes being the production of methanol, DME, or Fischer-Tropsch-fuels (Dieterich et al., 2020). In the current study, direct electrocatalytic conversion in a co-ionic membrane reactor was considered as conversion process. In this process, the CO_2 is converted into chemical energy carrier hydrocarbons. This approach is being investigated within the eCOCO$_2$ project by an interdisciplinary consortium (eCOCO$_2$, 2019). Overall, CO_2-based fuels offer a promising opportunity to reduce carbon emissions in the aviation sector and other industries. However, more research—regarding cost-effectiveness and scalability on the one hand, but also regarding societal perceptions and adoption requirements on the other hand—is needed to make them a viable alternative to conventional fossil fuels.

3 Perceptions and acceptance of CCU and CO_2-based fuels

Apart from the requirements and solutions for the technical implementation of CCU for fuel production, public perception and acceptance of the CCU technology and CO_2-based fuels must also be considered (e.g., Arning et al., 2019; Lutzke and Arvai, 2021). From the point of view of experts with domain-specific knowledge, the risks perceived by laypersons may not correspond to the factual, objective risks, but might be based on misconceptions or misunderstandings (Bostrom, 1997; Sjöberg, 1998). That is why a deeper understanding of these risk perceptions is important as they shape public perceptions and acceptance. This also applies to CO_2-based fuels, which must meet with positive public perception, acceptance, and ultimately willingness to use them to reach defossilization targets. However, public reaction to the introduction of renewables—both at the policy-strategic level and the local geographical level—has shown that these sustainable technological innovations are not always positively perceived, accepted, and (if possible) purchased or used (e.g., Zoellner et al., 2008; Batel, 2020).

Regarding the construct of "technology perceptions," the psychological concept of "perception" (Neisser, 1967) is used in the context of this study, which refers to the cognitive process to perceive, recognize, and be aware of something. Here, "technology perceptions" are defined as individual assessments of (dis) advantages and risks associated with a specific technology, its infrastructure, processes, and products, that—among other factors—influence and form acceptance (Offermann-van Heek et al., 2020). Based on Wüstenhagen et al. (2007), social acceptance of sustainable technological innovations can be assessed on three dimensions: 1) general socio-political acceptance of a technology or product, 2) local or community acceptance, which is about the acceptance of implementation in one's environment or community, and 3) market acceptance, which refers to the willingness of (potential) consumers or investors to buy or use a product. The current study focuses primarily on the market acceptance of CO_2-based aviation fuels. To define the concept of acceptance, we refer to a four-field scheme, which differentiates between an evaluative or attitude-related dimension (approval vs. rejection) and a behavior-related dimension (passive vs. active) (Schweizer-Ries, 2008). Since this paper examines the acceptance and willingness to use CO_2-based aviation fuels, *acceptance* is defined as the active or passive approval of CO_2-based aviation fuels. The *behavioral intention to use* is defined as the active willingness to book and take a flight fueled by CO_2-based fuels.

By now, there are a few studies that empirically examine the public perception of the CCU technology, its production processes, and of CO_2-based products such as fuels. In a direct comparison between the perception of the technological infrastructure and of CO_2-based products, the *CCU technology infrastructure* has been judged positively but still worse than the final CO_2-based fuel product (van Heek et al., 2017; Arning et al., 2019; Simons et al., 2021b). Considerable differences also exist between socio-political acceptance judgments related to the overall concept of CCU in terms of a climate-mitigation option and the local acceptance of CCU systems that would be implemented in the immediate neighborhood (Arning et al., 2020). Here, the general concept of CCU was evaluated significantly more positively than the deployment of a production facility in the immediate vicinity. The lower degree of local acceptance is also known from other infrastructure- and renewable energy technologies and is simplified as the *Not in my backyard* (*NIMBY*) effect (e.g., Devine-Wright, 2005). The NIMBY effect, however, is more than a mere rejection reaction, but is based on much more differentiated motives, such as trust, place attachment, or local identity (Devine-Wright, 2013b; van de Grift and Cuppen, 2022).

Considering the technology perceptions of benefits and risks that influence socio-political or local acceptance judgments, benefit perceptions are mainly shaped by perceived environmental benefits such as reduced CO_2 emissions, fossil resource savings, and reduced dependency on fossil resources (Jones et al., 2017; Linzenich et al., 2019). In addition, the economic benefits of CCU such as job creation are also perceived (Jones et al., 2014). In their acceptance model, Arning et al. (2020) showed that perceived benefits primarily influence socio-political acceptance of the CCU technology. However, risks are also perceived in connection with the CCU technology, which relate primarily to the areas of sustainability concerns, health- and environmental risks, and economic risks. Sustainability concerns about CCU technology are more pronounced than perceived health risks (Arning et al., 2016). In terms of sustainability concerns, it is doubted that the short-term storage of CO_2 in products can contribute to the reduction of CO_2 emissions. Moreover, CCU is perceived as a pretext for the energy-intensive fossil-based industry to continue emitting CO_2. Other sustainability concerns relate to the possible cannibalization of green subsidies for other, more sustainable technology innovations than CCU, and to postponing the problem of CO_2 emissions instead of addressing its causes (Jones et al., 2017; Arning et al., 2019). In terms of perceived environmental and health risk perceptions associated with CCU technology, risk perceptions relate primarily to the potential leakage of CO_2 during storage, transport, or production (Arning et al., 2019). Although a linear relationship with acceptance judgments could be proven for these perceptions, health- and environment-related risk perceptions are not elevated among the general public. In terms of economic risk perceptions, there are concerns that CCU technology could not be operated profitably due to the high energy requirements; public funding of this technology is strongly rejected (Zaunbrecher, et al., 2014; Arning, 2019).

The perceptions and acceptance of *CO_2-based products*, on the other hand, are more positive compared to evaluations of the CCU production technology. Product categories investigated so far are the carbonization of beverages (Lutzke and Arvai, 2021), plastic products (foam mattresses, Arning et al., 2018), building materials (insulation boards, Arning et al., 2021), fuels for passenger cars (Offermann-van Heek et al., 2020) or for aircraft fuels (Simons et al., 2021), with fuels as a potential CO_2-based product being preferred by the public in a direct comparison (Offermann-van Heek et al., 2018). As expected, the perception of CO_2 products is based on different risks and benefits than CCU technology evaluations, such as risk perceptions related to the technical maturity of the products, their lifespan compared to conventionally produced products, and the issue of disposal (van Heek et al., 2017).

For CO_2-based fuels for road transport or aviation, however, the empirical evidence is still very limited. Sustainable biofuels have been much better studied in terms of social acceptance, but the findings are characterized by the different raw materials (biogenic materials), production processes, and social debates (tank vs. plate-debate, e.g., Thompson, 2012) and cannot simply be transferred to the field of CO_2-based fuels.

With respect to CO_2-based fuels for road transport and aviation, it has been shown that laypersons perceive them as safer, more environmentally friendly, cleaner, and less toxic than conventional fossil fuels (Engelmann et al., 2020). The concept of using CO_2-based fuels is perceived by the public as an acceptable technology to support a sustainable mobility transition with low perceived risks regarding toxic effects, concerns about environmental pollution, and the perceived general harmfulness of CO_2-based fuels (Linzenich et al., 2022). Another barrier identified was respondents' perceptions of a higher price of CO_2-based fuels, which was assumed to result in increased ticket prices (Simons et al., 2021). In the context of sustainable aviation biofuels, Xu et al. (2022) revealed positive attitudes toward sustainable fuels, but the majority of participants were not willing to spend more money on carbon-neutral air travel. Other barriers are the very limited awareness and concerns about the safety of aviation fuels and their contribution to the environment (Filimonau et al., 2018).

A further but essential challenge in technology acceptance research is the "attitude-behavior" gap, i.e., the phenomenon that attitudes such as acceptance and behavioral intentions as well as the final actual target behavior often do not match (e.g., Claudy et al., 2013). Comparing studies on the perception, acceptance, and the willingness to use CO_2-based products, it is striking that the dependent variables to measure attitudes or behavioral intentions as target criteria have been operationalized very differently. In studies based on the Technology Acceptance Model (Davis, 1989), ratings of acceptance were collected and interpreted as a "target variable" for readiness or willingness to use innovative products. In more recent studies, the intention to use was measured *via* an anticipated willingness to buy or use (e.g., Arning et al., 2018), since a specific intention to use cannot be measured for products that are not yet available on the market. We are not aware of a study that captured and analyzed both facets, i.e., acceptance ratings as an attitudinal dependent variable and intention to use-ratings as a behavioral-oriented dependent variable.

3.1 Individual impact factors on social perceptions and acceptance

To gain a better understanding of why individuals react differently to technology innovations, either accepting them enthusiastically, rejecting them vehemently, or not reacting to them at all, social science research has been investigating a large number of individual factors for decades (e.g., Sun and Zhang, 2006; Arning and Ziefle, 2009; Huijts et al., 2012). These individual factors comprise sociodemographic factors (e.g., age, gender, or education), knowledge-related factors (e.g., domain-specific knowledge or perceived informedness), attitude-related factors (e.g., openness to innovations, environmental awareness, flight-related moral attitudes), behavior-related factors (e.g., the use of a technology), or perception-related factors consisting of perceived benefits and disadvantages of a technology.

In relation to socio-demographic factors, it was found for *age* that younger people were more positive towards sustainable technologies [e.g., for renewable technologies (Zaunbrecher et al., 2014; Bertsch et al., 2016), for CCUS technologies (Perdan et al., 2017) or electric vehicles (EVs) (Chen et al., 2020)], while older people reported lower benefits (Perdan et al., 2017) and higher risk perceptions (Zaunbrecher et al., 2014). The influence of *gender* was most visible in relation to risk perceptions, as women indicated higher risks for their own health and the environment when evaluating, e.g., the CCU technology and CO_2-based products (Perdan et al., 2017; Arning et al., 2018; Linzenich et al., 2019). Women also reported a lower socio-political and local acceptance of CCU production plants (Arning et al., 2020). In contrast, men reported a higher openness (Chen et al., 2020), higher acceptance (Ren et al., 2016), and stronger purchase interest (Chen et al., 2020) in sustainable technologies. *Education* is another influencing factor, although findings are contradictory. Higher education was found to be associated with higher awareness of sustainable technologies (Perdan et al., 2017), but also with higher risk perceptions (Ren et al., 2016; Arning et al., 2020) and negative attitudes toward energy infrastructure technologies (Devine-Wright, 2013a). *Income* tends to be associated with positive attitudes and higher purchase interest (Chen et al., 2020), though this factor is often confounded with education and domain-specific knowledge.

Because social science acceptance studies often occur in a national context, there is little knowledge of country-specific differences in perceptions and acceptance of sustainable technology innovations. In terms of EV use and car sharing, significant differences in technology ratings (ease of use, attitude toward using) between North America, Europe, and China were identified (Müller, 2019). Regarding the acceptance of hydrogen fuel cells, Bögel et al. (2018) conducted a survey in seven European countries. However, the study focused on the influence of prior knowledge and attitudes, so no detailed country-specific analysis was carried out.

The *awareness* or level of information about a technology also has a positive effect on the perception and acceptance of sustainable technologies. Subjectively perceived informedness positively influenced the acceptance of hydrogen storage (Zaunbrecher et al., 2016) or the willingness to pay for renewable electricity (Liu et al., 2013). With regard to risk perceptions, the findings are mixed; higher risk perceptions [for nuclear power technology (Zhu et al., 2016) or CCUS technologies (Perdan et al., 2017)], but also lower risk perceptions were measured for subjectively higher informedness (Zaunbrecher et al., 2016; van Heek et al., 2017).

In the field of *attitudinal factors*, environment-related attitudes are highly relevant predictors of perception and acceptance. Higher *environmental and climate change awareness* is associated with

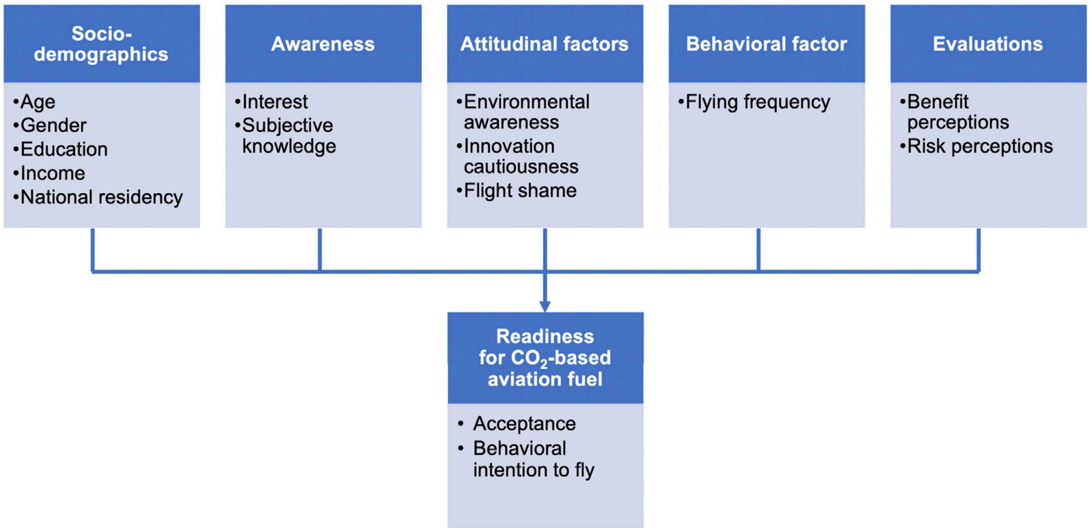

FIGURE 1
Conceptual framework of impact factors on CO_2-based aviation fuel readiness.

higher acceptance [e.g., for wind power (Devine-Wright, 2007) and electric cars (Chen et al., 2020)]. However, higher environmental and climate change awareness was also related to a more reactive attitude toward CO_2-based plastic mattresses (Arning, van Heek, et al., 2018). Individual *innovativeness* also acts as a moderating factor in the evaluation and uptake of sustainable technologies. When innovativeness was highly pronounced, levels of acceptance were higher as well, e.g., for the acceptance of smart meters (Alkawsi et al., 2021) or the willingness to use EVs (Khazaei, 2019). Another attitude-related factor that has been discussed recently is the feeling of shame when using less environmentally friendly means of transportation such as airplanes (Gunziger et al., 2022). Since "flight shame" is a rather novel phenomenon (Chiambaretto et al., 2021), there is not yet enough research on the influence of flight shame on the perception and acceptance of sustainable fuels.

Individual *mobility behavior* is another factor influencing the perception and acceptance of alternative transport and drive technologies. Regarding the use of EVs it was shown that own usage experiences are associated with a more positive attitude and higher purchase intention (Larson et al., 2014). Conversely, a higher individual mileage per year was associated with lower acceptance of alternative transportation (Jansson and Rezvani, 2019). However, there is still limited knowledge of the influence of flight behavior or habits on the acceptance of CO_2-based fuels.

Evaluations of *perceived risks and benefits* are the strongest overall influencing factor on the acceptance of sustainable technologies, their infrastructure, and end products. Benefit perceptions of CCU technology and products were identified as mainly environmentally-related reduction of CO_2 emissions, saving of fossil resources (Arning et al., 2017), and economic benefits [job creation (Jones et al., 2014)]. Overall, benefit perceptions have a stronger effect on the general or socio-political acceptance of technologies (Davis, 1989; Huijts et al., 2012; Arning et al., 2020), whereas risk perceptions have a stronger effect on the local acceptance of infrastructure technology (e.g., for CCU production facilities, Arning et al., 2020). Risk perceptions are related to environmental or health risks (e.g., leakage of CO_2 during storage, transport, or use of products), sustainability concerns (greenwashing, cannibalization of investments in other sustainable technologies), or safety risks (technical reliability and maturity of the production technology and products) (Arning et al., 2019; Lutzke and Arvai, 2021).

In conclusion, the influence of individual factors on the perception and evaluation of sustainable technologies has been thoroughly studied with respect to different technology domains and individual factors considered, but little is known about public readiness for CO_2-based aviation fuels and the impact of individual factors in a cross-European comparison.

3.2 Research approach and hypotheses

The current study aims to investigate the public's readiness (acceptance as well as behavioral intention) to use CO_2-based aviation fuels in four European countries. The novelties of our study are:

a) A wide range of potential impact factors is statistically analyzed, i.e., sociodemographic factors, awareness, attitudinal factors (innovation cautiousness, environmental awareness, flight shame), behavioral factors (flight habits) and technology evaluations in terms of benefit and risk perceptions of CO_2-based fuels. We applied regression analyses to explore if and to what extent the impact factors predict acceptance of and the behavioral intention to fly with CO_2-based fuels.
b) A cross-European perspective is pursued. The selection of countries is linked to the nationalities represented in the eCOCO$_2$ project, thus having substantial national research

interest in the CCU technology and high motivation to foster the technology.

c) Empirical measurements are applied that include both and differentiate between two relevant adoption indicators, i.e., a) attitudinal ratings of CO_2-based fuel acceptance and b) the behavioral intention to fly with CO_2-based fuels.
d) Detailed insights on major drivers and barriers on CO_2-based aviation fuel readiness are delivered.

Based on the potential impact factors on CO_2-based aviation fuel readiness, general research questions and specific hypotheses were derived. For an overview of the conceptual framework of impact factors investigated in this study see Figure 1.

Research Question 1: Do the four European countries differ regarding the analyzed impact factors? In this context, we analyze country differences exploratorily since no specific country-related hypothesis can be formulated.

Research Question 2: Which *sociodemographic factors* are associated with CO_2-based aviation fuel readiness in terms of a) acceptance and b) behavioral intention to fly with CO_2-based aviation fuels?

H2.1: Younger individuals show higher levels of a) acceptance and b) behavioral intention to fly with CO_2-based aviation fuels.

H2.2: Men show higher levels of a) acceptance and b) behavioral intention to fly with CO_2-based aviation fuels.

H2.3: Individuals with a higher education show higher levels of a) acceptance and b) behavioral intention to fly with CO_2-based aviation fuels.

H2.4: Individuals with a higher income show higher levels of a) acceptance and b) behavioral intention to fly with CO_2-based aviation fuels.

Research Question 3: Is *awareness* for the topic of CO_2-based fuels associated with CO_2-based aviation fuel readiness?

H3.1: Individuals with a higher interest in CO_2-based fuels show higher levels of a) acceptance and b) behavioral intention to fly with CO_2-based aviation fuels.

H3.2: Individuals with a higher subjective knowledge of CO_2-based fuels show higher levels of a) acceptance and b) behavioral intention to fly with CO_2-based aviation fuels.

Research Question 4: How are *attitudinal factors* related to CO_2-based aviation fuel readiness?

H4.1: Individuals with higher levels of environmental awareness show higher levels of a) acceptance and b) behavioral intention to fly with CO_2-based aviation fuels.

H4.2: Individuals with lower levels of innovation cautiousness show higher levels of a) acceptance and b) behavioral intention to fly with CO_2-based aviation fuels.

H4.3: Individuals with lower levels of flight shame show higher levels of a) acceptance and b) behavioral intention to fly with CO_2-based aviation fuels.

Research Question 5: How are *behavioral factors* related to CO_2-based aviation fuel readiness?

H5.1: Higher flying frequencies are positively associated with higher levels of a) acceptance and b) behavioral intention to fly with CO_2-based aviation fuels.

Research Question 6: How are CO_2-based aviation fuel *evaluations* (in terms of risk- and benefit perceptions) related to CO_2-based aviation fuel readiness?

TABLE 1 Descriptive data on the national subsamples in terms of age, gender, education, and income.

Nation	Germany	Spain	Netherlands	Norway
N	543	545	549	491
Age in years				
M	45.0	45.4	44.8	45.0
SD	15.2	13.6	15.0	14.4
Gender in %				
Female	49.9	54.9	50.8	52.0
Male	50.1	45.1	49.2	48.0
Income in %				
<1.000 €	15.2	28.7	15.2	26.7
1.000–2.000 €	28.6	43.2	27.9	53.2
2.000–3.000 €	23.0	17.4	26.3	14.1
3.000–4.000 €	19.1	7.5	18.8	3.3
4.000–5.000 €	9.1	2.1	7.1	1.8
5.000 € or more	5.1	1.1	4.6	1.0
Education in %				
Low	15.8	28.6	14.8	7.1
Medium	55.4	31.6	45.5	51.3
High	28.7	39.8	39.7	41.6

H6.1: CO_2-based aviation fuel benefit perceptions are positively associated with a) acceptance and b) behavioral intention to fly with CO_2-based aviation fuel.

H6.1: CO_2-based aviation fuel risk perceptions are negatively associated with a) acceptance and b) behavioral intention to fly with CO_2-based aviation fuel.

4 Materials and methods

An empirical study was conducted in four European countries (Germany, Norway, the Netherlands, and Spain) to investigate public CO_2-based aviation fuel readiness in terms of acceptance and behavioral intention and the influence of socio-demographic and attitudinal factors as well as and flying frequency as behavioral factor. The sample, survey structure and variables, and data analysis techniques are detailed below.

4.1 Sample

Several measures were taken to ensure high data quality. After data collection, the initial dataset (N = 9,738) was filtered for respondents that were excluded during participation because of full quotas, early dropping out, speeding (i.e., response time below 35% of median duration), and incorrect answering to at least one of two attention control questions. Additionally, complete data sets with an internally inconsistent answering behavior (e.g., “straightliners”) were omitted. The sample consisted of a total of $N = 2{,}187$ participants, 52% of whom were female ($n = 1{,}135$) and 48% male ($n = 1{,}052$). Because the survey was collected in parallel in four European countries, the sample consisted of *n* = 543 German, *n* = 545 Spanish, *n* = 549 Dutch, and *n* = 550 Norwegian participants (25% each of the total sample). Fixed age ratios were used in the survey to allow a country-specific representative age distribution to be mapped. The mean age was M = 45 years (SD = 14.5 years), with a range between 18 and 70 years. The educational level attained (based on the International Standard Level of Education, ISCED) was in the medium (46%, *n* = 1,005) or high range (37% *n* = 820). For 17% (*n* = 362), the educational level was in a low range. See Table 1 for descriptive data on the national subsamples in terms of age, gender, education, and income.

4.2 Survey structure and variables

To investigate the research hypotheses, a quantitative online questionnaire was created using the Qualtrics questionnaire software. The German and Dutch versions of the questionnaire were developed by native speakers in the research team, for the Norwegian and Spanish versions a professional translation agency was contracted. Before the questionnaires were used, they were checked by native speakers of the respective languages for the correctness of translation and comprehensibility. The questionnaire was also reviewed by the ethics committee of RWTH Aachen University for ethical acceptability and approved for empirical use.

Constructs and items were selected based on 1) Established and validated scales used in previous surveys by the research group (e.g., Simons et al., 2021), 2) A literature review of survey scales used in the context of attitudes towards sustainable technology innovations, and 3) Input from technical experts that was integrated into the formulation of novel items. The questionnaire consisted of several modules and instructional sections, which are listed below Figure 1. At the beginning of the survey, participants answered screening questions related to age, gender, education, and region to allow for representative sampling. Provided the quota requirements were met, participants received the introductory instruction on the topic of the survey and were informed of their rights under the Data Protection Regulation (Schwartz, 2020). On average, it took participants 23.2 min (SD = 9.6 min) to complete the survey. An English version of all items included in the analysis and descriptive item statistics can be found in Supplementary Appendix A.

Survey data collection was conducted in the fall of 2020. A market research agency was commissioned with the recruitment of the sample, which collected the data from its online panel in accordance with the quota specifications and incentivized the participants on their terms. The instructional texts were developed in cooperation with technical experts from the CCU field and checked in pretests for factual correctness and comprehensibility for laypeople. An English version of the instruction provided is presented in Supplementary Appendix B. The factors and constructs collected in the questionnaire are described in detail below.

Item measurements used six-point scales with 0 coded for the most negative response and 5 coded for the most positive response. When measuring constructs with multiple items, items were presented in randomized order ruling out sequence effects. To avoid response tendencies in the multiple-item measurement of constructs, items with different polarities were used. During data preparation and construct formation, the items that were not correctly polarized were reversed so that a low level of the construct corresponded to low values and *vice versa*.

In building the constructs, the internal reliability of the items was calculated (Cronbach's alpha) and the items with reliability coefficients <0.7 were removed in the construct formation. For constructs that were measured with several items, a construct score was formed from the mean value of the respective items. This mean construct score was then used in the descriptive-, variance-, and regression analyses.

4.2.1 Individual factors

In the first section, individual factors such as *sociodemographic* information (age, gender, education, income) were assessed. Because education systems differ across countries, a grouping variable was created for the education of the respondents. Depending on the national education system, we asked about the highest level of education attained in each of the four countries. In the data processing, the information on education was recoded according to the International Standard Classification of Education (ICSED) into three categories (0 = low, 1 = medium, 2 = high education) (Eurostat Statistics Explained, 2011). Respondents also indicated their approximate net monthly income, which was coded into five categories (0 = < 1,000€, 1 = 1,001–2000€, 2 = 2001–3,000€, 3 = 3,001–4,000€, 4 = 4,001–5,000€, 5 = 5,001€ or more).

Secondly, the *awareness* of CO_2-based aviation fuel in terms of interest and subjective knowledge was measured (Cronbach's alpha = 0.7, two items).

Thirdly, *several attitudinal factors* such as innovation cautiousness, environmental awareness, and flight shame were measured. *Innovation cautiousness* (Cronbach's alpha = 0.7, two items) described the individual reluctance to test and use innovative technologies, e.g., *"Before I consider using a new technology, I want to experience if others use it."* The construct of *environmental awareness* (Cronbach's alpha = 0.7, four items) included concerns about environmental damage to future generations, the perceived impact of CO_2 emissions on the climate, the impact of economic growth on the environment, and individual environmentally friendly behaviors, e.g., *"It worries me when I think about in what kind of environment future generations must most likely live."* The construct *flight shame* (Cronbach's alpha = 0.7, three items) measured the bad conscience due to environmental reasons to fly with an airplane, e.g., *"I have a bad conscience when I fly with an airplane because flying is damaging for the environment."*

Fourthly, as *a behavioral* factor, the individual *flying frequency* was measured. Respondents were asked about the frequency of short-distance flights (up to 2 h), medium-distance flights (up to 3.5 h), and long-distance flights (>3.5 h) for private and job-related purposes on a rating scale ranging from 0 = "never" to 5 = "a few times a week." A flying frequency score was calculated by the sum of the respective indications of flight distance and flight purpose (private or business). The maximum of the score flying frequency score was 30.

4.2.2 Evaluations of CO_2-based aviation fuels

The next and fifth section of the questionnaire dealt with the evaluation of CO_2-based aviation fuel in terms of *risk and benefit* *perceptions*. Participants had to indicate their agreement or disagreement with several benefits and risks of CO_2-based aviation fuels.

A factor analysis revealed two underlying factors for *risk perception*: first, health and environmental risk perceptions, and second, risk perceptions regarding the quality and technological maturity of CO_2-based aviation fuel. Based on the results of the factor analysis, two risk perception scores were built: *environmental- and health*-related risk perceptions (Cronbach's alpha = 0.9, two items), e.g., *"I think that* CO_2*-based fuels are damaging for the environment,"* and *product quality- and maturity*-related risk perceptions (Cronbach's alpha = 0.7, two items), e.g., *"I am afraid that the use of* CO_2*-based fuels poses a safety risk because I think that existing motors have not been built for them."* Bivariate correlations showed that both risk perception factors were positively associated ($r = .22$, $p < 0.001$), i.e., higher risk perceptions of negative environmental and health effects are associated with higher perceived risks on product quality and maturity.

For *benefit perceptions* of CO_2-based aviation fuel, the factor analysis revealed one factor without any subdimensions (Cronbach's alpha = .8, five items), which comprised benefits of fuel use in terms of price, environmental-friendliness, and reduced CO_2-emissions, e.g., *"I think that* CO_2*-based fuels are beneficial for the environment due to reduced emissions."*

Risk- and benefit perceptions were negatively correlated (fuel benefit perceptions and environmental- and health risk perceptions: $r = -.58$, $p < 0.001$; fuel benefit perceptions and product quality and maturity perceptions: $r = -.15$, $p < 0.001$).

4.2.3 CO_2-based aviation fuel readiness

The sixth and final part of the questionnaire asked for CO_2-based aviation fuel readiness among respondents, which comprised ratings of acceptance and behavioral usage intentions for CO_2-based aviation fuel. The construct of CO_2-based aviation fuel acceptance (Cronbach's alpha = 0.7, two items) comprised the support and relative preference of CO_2-based fuels for air travel, e.g.," *I support the use of* CO_2*-based fuels for air travel."* The behavioral intention (Cronbach's alpha = 0.7, two items) referred to the willingness to book and fly with CO_2-based fuels, e.g., *"The next time I am booking a flight, I am planning to consciously choose for a flight that is driven by* CO_2*-based fuels* (*when such an option is available*)."

4.3 Statistical analysis

Data was statistically analyzed by using descriptive statistics to analyze sample characteristics and the distribution of Likert-scale ratings, bivariate correlations to analyze relationships between the impact factors, MANOVAS to test differences in impact factors between the four European countries, and hierarchical regression analyses to test the relationship of the predictors with the CO_2-based aviation fuel readiness criteria (acceptance and behavioral intentions).

For the MANOVAs, the correctness of the distribution assumptions was checked, and—in case of violation—the corrected values (Pillai values) are reported. A p-value <0.05 was used to indicate statistical significance. The statistical analysis was computed by using SPSS Version 28.

The hierarchical regression method was chosen, because it allows to investigate the incremental influence of the impact factors examined here, by accounting for other factor's impact. Unlike a single stepwise regression, in which all factors are entered at the same time and the selection of predictors and estimation of influence weights may be biased, the hierarchical regression allows to estimate the added value of predictors and to determine their potential unique contribution in explaining the variance of CO_2-based aviation fuel readiness (Hair, 2011). In the hierarchical regression analyses, the blocks of predictors were entered in the following order:

- Step 1 (method: enter): Individual sociodemographic factors (age, gender, education, income);
- Step 2 (method: enter): Awareness in terms of subjective interest and subjective knowledge about CO_2-based fuels;
- Step 3 (method: enter): Attitudinal factors such as innovation cautiousness, environmental awareness, and flight shame;
- Step 4 (method: enter): The flying frequency as a behavioral factor;
- Step 5 (method: enter): Evaluations in terms of risk- and benefit perceptions;
- Step 6 (method: enter): CO_2-based aviation fuel readiness, indicated by acceptance and the behavioral intention to fly with CO_2-based fuels.

4.4 Regression diagnostics

Before the regression analysis was conducted, the assumptions of the regression were tested for linearity, homoscedasticity, multicollinearity, and normality (Hair, 2011). Frequency distribution analyses and reliability diagnostics of construct scales were obtained. To analyze the relationships among the variables, Pearson product-moment correlations were performed. Correlation analyses showed that the different predictors were not highly correlated. Collinearity analysis showed that the variance inflation factors (VIFs) of the regression models were in the range of 1.0–1.8, i.e., below the critical parameter of 10 (Hair, 2011), so multicollinearity between variables could be ruled out. After the selection of the respective regression models, further assumptions of linear regression were tested. The Durbin-Watson-Statistic was 1.992 (for the hierarchical regression model predicting CO_2-based aviation fuel acceptance) and 1.987 (for the hierarchical regression model predicting the behavioral intention), which indicates that the assumption of independent errors was met. Model fit was proven by ANOVAs, i.e., both models significantly improved the prediction of the outcome variable (for the final model predicting acceptance: $F(16, 2047) = 126.5$, $p < 0.001$; for behavioral intention: $F(16, 2047) = 87.9$, $p < 0.001$).

A visual inspection of the diagnostic plots was also performed to check for normality. All models of the residuals were examined. The histogram of the standardized residuals was approximately normal for both regression models, but slightly right skewed. Inspection of the P-P and Q-Q plots of the residuals revealed that the residuals were near normal with no extreme deviations from the expected value. The plot of the residuals *versus* the fitted values showed some

TABLE 2 Mean and standard deviations for income and education in the four European countries.

	Income		Education	
Nationality	M	SD	M	SD
DE	1.9	1.4	1.1	0.7
ES	1.2	1.1	1.1	0.8
NL	1.9	1.3	1.2	0.7
NO	1.0	0.9	1.3	0.6

Income categories: 0 = < 1,000€, 1 = 1,001–2000€, 2 = 2001–3,000€, 3 = 3,001–4,000€, 4 = 4,001–5,000€, 5 = 5,001€ or more; education categories (according to ICSED): 0 = low, 1 = medium, 2 = high; nationality: DE = Germany, ES = Spain, NL = Netherlands, NO = Norway.

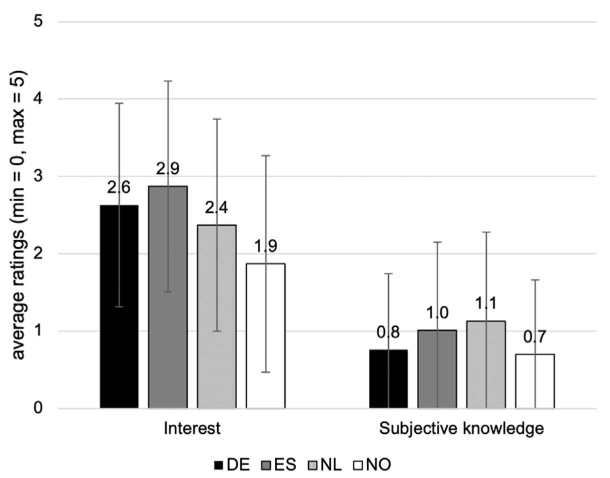

FIGURE 2
Average ratings of awareness factors (interest, subjective knowledge) in the four countries (DE = Germany, ES = Spain, NL = Netherlands, NO = Norway). Bars indicate standard deviations.

outliers with a consistent variation and variance and that the residuals were normally distributed.

5 Results

5.1 Descriptive and country-specific analyses

First, descriptive statistics, non-parametric t-Tests and MANOVAs were calculated to gain an overview of the manifestation of the impact factors in the respective countries and to analyze country-specific differences.

In terms of **sociodemographic variables**, significant differences were found between countries in income and education ($F(12, 6,129) = 25.2$, $p < 0.001$, $\eta = 0.47$, Table 2). Compared to the income data of German and Dutch respondents, the respondents from Spain and Norway reported a significantly lower income ($F(3, 2044) = 81.7$, $p < 0.001$, $\eta = 0.11$). Significant differences were also found for education based on ISCED (0 = low, 1 = medium, 2 = high) ($F(3, 2044) = 12.1$, $p < 0.001$, $\eta = 0.02$). Educational attainment was the highest in Norway, followed by the Netherlands. It was the lowest in Germany and Spain. There were no differences in age and gender due to the settings of the sampling quota.

Regarding the **awareness** of CO_2-based aviation fuels (see Figure 2) a slightly lowered *interest* [M = 2.4, SD = 1.4, a significant difference from the midpoint of the scale (which was 2.5) ($t_{2186} = -2.2$, $p < 0.001$)] as well as a low *subjective knowledge* level on the issue of CO_2-based fuel production [M = 0.9, SD = 1.1, a significant difference from the midpoint of the scale ($t_{2186} = -69.5$, $p < 0.001$)] in the total sample were found. Interest and subjective knowledge were positively correlated ($r = .23$, $p < 0.001$), i.e., the higher the interest in CO_2-based aviation fuel, the higher the subjective knowledge.

A MANOVA revealed a highly significant main effect of nationality in CO_2-based aviation fuel *interest* ($F(6, 4,366) = 35.1$, $p < 0.001$, $\eta = 0.05$). Interest was the highest in Spain compared to the other European countries ($F(3, 2183) = 54.0$, $p < 0.001$, $\eta = 0.07$) and the lowest in Norway. Subjective knowledge also significantly differed in the four countries ($F(3,2183) = 20.5$, $p < 0.001$, $\eta = 0.03$), with the highest knowledge levels in the Netherlands, followed by Spain. The lowest knowledge levels were present in Germany and Norway.

The analysis of **attitudinal factors**, i.e., innovation cautiousness, environmental awareness, flight shame, in the four countries revealed positive levels of *environmental awareness* [M = 3.5, SD = 0.9, significant difference from the midpoint of the scale ($t_{2186} = 47.8$, $p < 0.001$)], a positively pronounced *innovation cautiousness* [M = 2.9, SD = 0.9, significant difference from the midpoint of the scale ($t_{2186} = 16.9$, $p < 0.001$)] and slightly lowered *flight shame* levels [M = 2.4, SD = 0.5, but significantly below the midpoint of the scale ($t_{2186} = -11.5$, $p < 0.001$, Figure 3)]. Thus, respondents perceived themselves as environmentally aware, as being rather reluctant in trying out innovations, and tended not to be ashamed when flying by plane.

Looking at associations between the three attitudinal factors, higher levels of environmental awareness were positively related to higher levels of flight shame ($r = 0.47$, $p < 0.001$). Weaker, but still positive associations were found for environmental awareness and innovation cautiousness ($r = 0.1$, $p < 0.001$) as well as flight shame and innovation cautiousness ($r = 0.09$, $p < 0.001$).

At the country level, there were significant differences between the attitudinal factors ($F(9, 6,549) = 44.8$, $p < 0.001$, $\eta = 0.06$, Table 3). Environmental awareness was the highest in Spain, followed by Germany and the Netherlands; the lowest environmental awareness levels were reported in Norway ($F(3, 2183) = 86.0$, $p < 0.001$, $\eta = 0.1$).

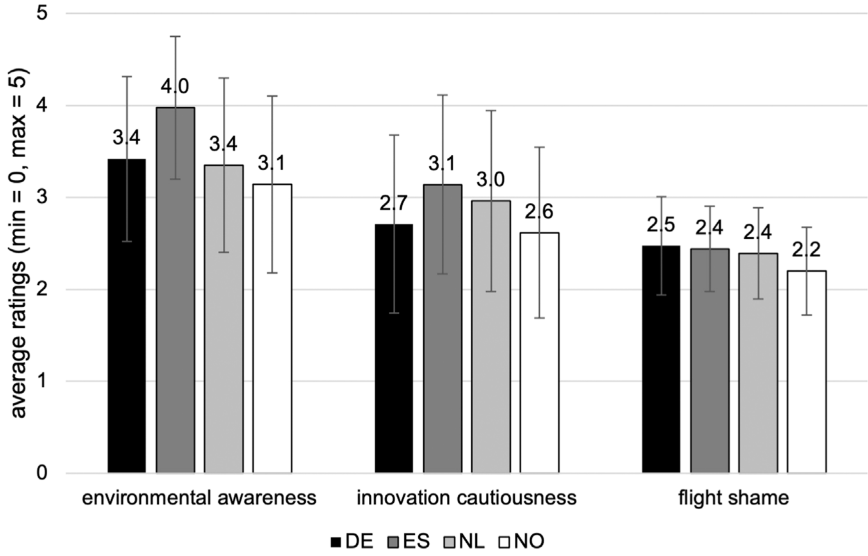

FIGURE 3
Average ratings of attitudinal factors (environmental awareness, innovation cautiousness, flight shame) in the four countries (DE = Germany, ES = Spain, NL = Netherlands, NO = Norway). Bars indicate standard deviations.

TABLE 3 Results of the hierarchical regression analysis on acceptance ratings.

Variables	Model 1	Model 2	Model 3	Model 4	Model 5
Step 1: sociodemographic factors					
Age	−0.02	−0.02	−0.01	−0.01	−0.03
gender	0.01	−0.03	0.00	0.00	0.02
education	0.12***	0.08***	0.06**	0.06**	0.05**
income	0.04	0.02	0.04	0.04	0.03
Germany	−0.09***	−0.06*	−0.01	−0.01	0.03
Netherlands	−0.12***	−0.06*	0.00	0.00	0.01
Norway	−0.15***	−0.05	0.04	0.04	−0.06**
Step 2: awareness					
interest		0.33***	0.28***	0.28***	0.07***
subj. knowledge		−0.03	−0.03	0.02	0.02
Step 3: attitudinal factors					
innovation cautiousness			0.00	0.03	−0.01
environmental awareness			0.26***	0.26***	0.17***
flight shame			0.00	−0.03	0.07***
Step 4: behavioral factor					
flying frequency				0.00	−0.01
Step 5: evaluations					
benefit perceptions					0.45***
environmental- and health risk perceptions					−0.12***
technical quality and -maturity risk perceptions					−0.12***

Dependent Variable: CO_2-based fuel acceptance.
Asterisks indicate significant differences (*p < 0.05, **p < 0.01, ***p < 0.001).

Innovation cautiousness was the highest in Spain, followed by the Netherlands and Germany. The lowest innovation cautiousness levels were found in Norway ($F(3, 2183) = 33.5$, $p < 0.001$, $\eta = 0.04$). Flight shame levels were the highest in Germany, followed by Spain and Netherlands, and the lowest levels were present in Norway ($F(3, 2183) = 34.1$, $p < 0.001$, $\eta = 0.05$).

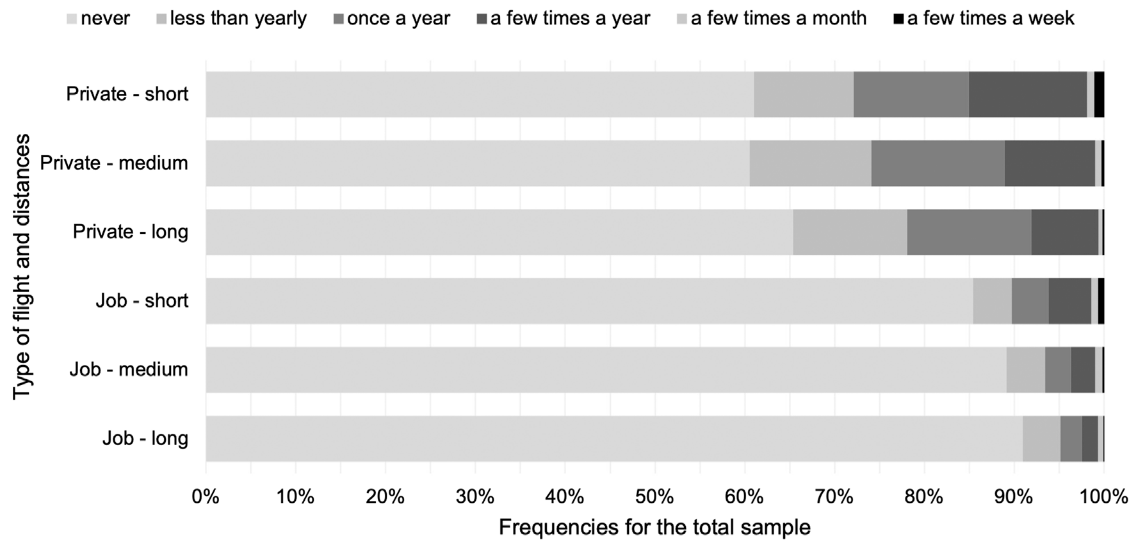

FIGURE 4
Flight frequency for professional and private short-, medium- and long-haul flights in the total sample.

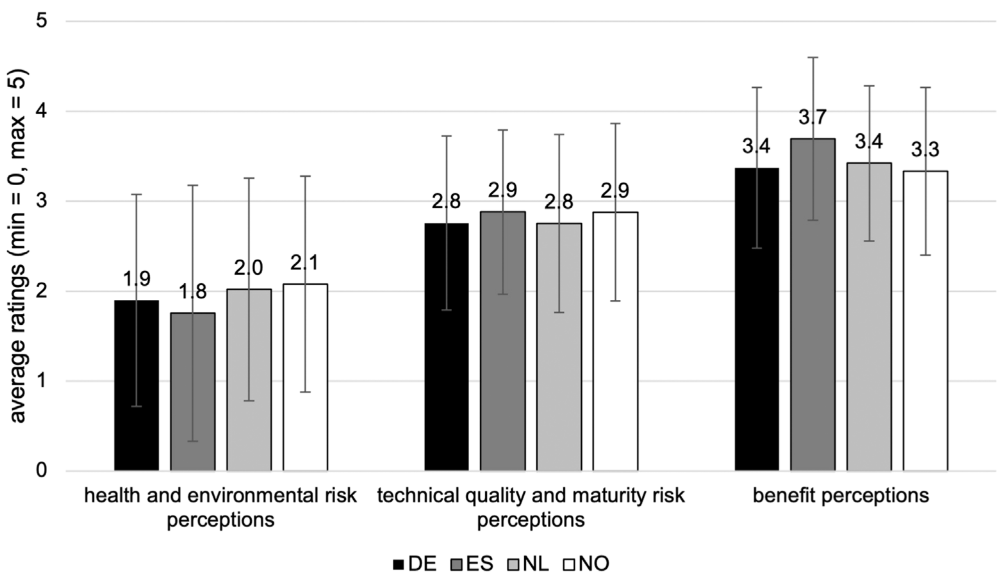

FIGURE 5
Average ratings of CO_2-based fuel evaluations (risk- and benefit perceptions) in the four countries (DE = Germany, ES = Spain, NL = Netherlands, NO = Norway). Bars indicate standard deviations.

Looking at **behavioral factors**, the analysis of *flight frequency* showed that the sample flew rather rarely (see Figure 4, M = 3.02, SD = 4.05, data refer to the analysis of the flight frequency index (sum of the frequency data for professional and private short-, medium- and long-haul flights), which was max. 30).

From Figure 4 it can be seen that a large proportion of respondents (40%, n = 877) stated that they never flew. The standard deviation, however, indicates large deviations in flight frequencies. An ANOVA with the flight frequency index as the dependent variable showed that there were highly significant differences between the samples of the four countries ($F(3, 2183) = 25.4$, $p < 0.001$, η = 0,03). Norwegians flew significantly more frequently than all other three countries ($M_{NO} = 4.3$, SD = 4.1, $M_{ES} = 2.8$, SD = 4.2, $M_{NL} = 2.8$, SD = 4.1), while Germans reported flying the least ($M_{DE} = 2.3$, SD = 3.5).

The analysis of **evaluations** in terms of risk- and benefit perceptions of CO_2-based fuels (see Figure 5) showed low perceived *health- and environmental risk perceptions* [M = 1.94, SD = 1.27, significantly lower than the midpoint of the scale ($t_{2186} = -20.7$, $p < 0.001$)] and comparably higher risk

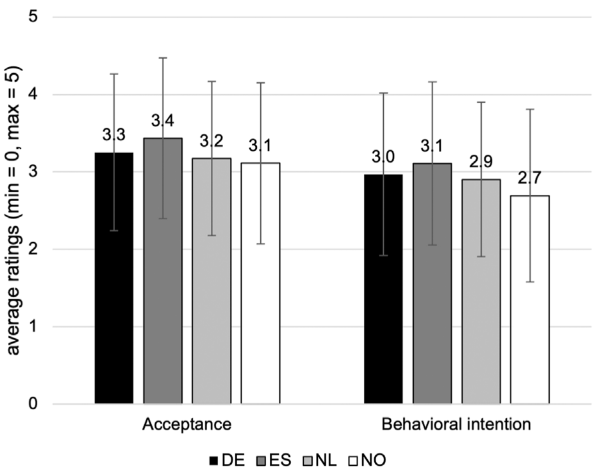

FIGURE 6
Average ratings of CO_2-based fuel readiness (acceptance and behavioral intention) in the four countries (DE = Germany, ES = Spain, NL = Netherlands, NO = Norway). Bars indicate standard deviations.

perceptions regarding *technical quality and maturity* of fuels [M = 2.82, SD = 0.97, significantly higher than the midpoint of the scale (t_{2186} = 15.4, p < 0.001)]. On the other hand, *benefit perceptions* of CO_2-based fuels were positively pronounced [M = 3.1, SD = 0.88, significantly higher than the midpoint of the scale (t_{2186} = 33.4, p < 0.001)].

Correlational analyses showed that risk- and benefit perceptions were negatively associated (r = −0.48, p < 0.001) for benefit perceptions and environmental- and health risk perceptions, as well as for benefit perceptions and risk perceptions on technical quality and maturity (r = −0.16, p < 0.001). Both risk perception dimensions were weakly positively related, i.e., with higher risk perceptions regarding health and the environment, there were also higher risk perceptions regarding the product quality and technical maturity of CO_2-based fuels (r = 0.22, p < 0.001).

Differences existed in the samples of the four countries for both risk and benefit perceptions (F(9, 6,549) = 8.33, p < 0.001, η = 0.01). The highest *health- and environmental risk perceptions* were expressed in Norway and the Netherlands, followed by Germany and—with the lowest risk perceptions—Spain (F(3, 2183) = 7.1, p < 0.001, η = 0.01). Risk perceptions on *technical quality and maturity* of fuels were the highest in Spain and Norway and the lowest in Germany and the Netherlands (F(3, 2183) = 3.1, p < 0.05, η = 0.00). *Benefit perceptions* were the highest in Spain, followed by the Netherlands and Germany, and the lowest in Norway (F(3, 2183) = 18.2, p < 0.001, η = 0.02).

In a final step, CO_2-based fuel **readiness** (see Figure 6) was analyzed in terms of acceptance and behavioral intention to fly. In the overall sample, there was a positively pronounced acceptance [M = 3.2, SD = 1.0, significantly higher than the midpoint of the scale (t_{2194} = 33.9, p < 0.001)] and a positively pronounced behavioral intention to fly with CO_2-based fuels [M = 2.9, SD = 1.1, significantly higher than the midpoint of the scale (t_{2186} = 18.4, p < 0.001)]. Both readiness dimensions were strongly positively correlated, i.e., higher acceptance levels were associated with higher usage intention levels (r = 0.73, p < 0.001).

A MANOVA revealed highly significant differences in readiness in the four countries (F(6, 4,366) = 8.8, p < 0.001, η = 0.01). Acceptance was highest in Spain, followed by Germany and the Netherlands, and lowest in Norway (F(3, 2183 = 14.7, p < 0.001. η = 0.02). Overall, the intention to use CO_2-based fuels was lower than acceptance ($M_{acceptance}$ = 3.2, SD = 1.0, $M_{Behav. Intention}$ = 2.9, SD = 1.0, F(1, 2183) = 395.5, p < 0.001, η = .5). The behavioral attention to book and fly with CO_2-based fuels was highest in Spain, followed by Germany and the Netherlands, and lowest (but still positive) in Norway (F(3, 2183 = 10.4, p < 0.001. η = 0.01)).

To sum up, the sociodemographic variables showed significant differences between countries, with the highest education attainment reported in Norway and the lowest income reported in Spain and Norway. The interest in and knowledge on CO_2-based aviation fuels was slightly low, but positively correlated. Nationality significantly affected the interest and knowledge levels, with the highest interest in Spain and the highest knowledge levels in the Netherlands. Respondents reported high environmental awareness, innovation cautiousness, and low flight shame levels. Environmental awareness was highest in Spain, innovation cautiousness was highest in Spain, and flight shame was highest in Germany. The flight frequency index showed that the sample flew rather rarely.

5.2 Regression analysis

After the analysis of the individual constructs showed significant differences for the four countries considered, country-specific hierarchical regressions were calculated in the next step to predict 1) the acceptance of CO_2-based aviation fuel (Section 5.2.1) and 2) the behavioral intention to fly with CO_2-based fuels (Section 5.2.2) with the sociodemographic, attitudinal, evaluation-related, and behavioral impact factors (model summaries in Table 3, 4, for detailed model information see Supplementary Tables S5, S6).

5.2.1 Prediction of CO_2-based fuel acceptance

To predict the acceptance of CO_2-based fuel and to answer RQ2 **model 1** was calculated. It revealed that **sociodemographic factors** explained 3% of the variability of CO_2-based fuel acceptance (adjusted R^2 = 0.03; F(7, 2047) = 9.4, p < 0.001, Table 3). Among the entered sociodemographic variables, respondents with higher levels of education showed higher CO_2-based fuel acceptance levels (β = 0.12, p < 0.001) and residents of Germany (β = −0.09, p < 0.001), the Netherlands (β = −0.12, p < 0.001) and Norway (β = −0.15, p < 0.001) showed lower acceptance levels. Age, gender, and income were no significant predictors of CO_2-based fuel acceptance. The variable Spain was excluded as a predictor in the model.

The inclusion of CO_2-based fuel **awareness** (addressed in RQ3) in **model 2** resulted in a statistically significant model (adjusted R^2 = 0.12; F(9, 2047) = 32.4, p < 0.001), with a significant improvement in R^2 from 3% to 12% (F(2, 2038) = 109.2, p < 0.001). Among the entered variables education (β =

TABLE 4 Results of the hierarchical regression analysis on the behavioral intention to fly with CO_2-based fuels.

Variables	Model 1	Model 2	Model 3	Model 4	Model 5
Step 1: sociodemographic factors					
age	−0.1***	−0.09***	−0.08***	−0.07***	−0.09***
gender	−0.01	−0.05*	−0.03	−0.03	−0.02
education	0.1***	0.05*	0.04	0.03	0.02
income	0.06*	0.04	0.06**	0.04	0.03
Germany	−0.08**	−0.04	0.02	0.03	0.06*
Netherlands	−0.1***	−0.04	0.02	0.03	0.04
Norway	−0.18***	−0.07*	0.02	0.01	0.02
Step 2: awareness					
interest		0.35***	0.31***	0.28***	0.14***
subj. knowledge		0.02	0.03	−0.03	0.05**
Step 3: attitudinal factors					
innovation cautiousness			0.03	0.00	0.02
environmental awareness			0.26***	0.26***	0.18***
flight shame			−0.03	0.00	0.02
Step 4: behavioral factor					
flying frequency				0.06**	0.06**
Step 5: evaluations					
benefit perceptions					0.39***
environmental- and health risk perceptions					−0.09***
technical quality and -maturity risk perceptions					−0.12***

Dependent Variable: Behavioral intention to fly with CO_2-based fuels.
Asterisks indicate significant differences (*$p < 0.05$, **$p < 0.01$ =, ***$p < 0.001$).

0.08, $p < 0.001$), interest ($\beta = 0.33$, $p < 0.001$), and residency in Germany ($\beta = -0.06$, $p < 0.05$) and the Netherlands ($\beta = -0.06$, $p < 0.05$) exerted predictive utility regarding CO_2-based fuel acceptance. Thus, the higher the education and interest in CO_2-based fuel, the higher the levels of CO_2-based fuel acceptance. Residents of Germany and the Netherlands reported lower acceptance levels. The demographic variables age, gender, and income remained to be insignificant in model 2, Norwegian residency became insignificant as a predictor in model 2. The newly entered variable subjective knowledge was also not significant.

In **model 3**, the entry of **attitudinal factors** (addressed in RQ4) led to a significant model, that explained 18% of the variance (adjusted $R^2 = 0.18$; $F(12, 2047) = 38.0$, $p < 0.001$) and to an improvement in the explained variance of 6% ($F(3, 2035) = 48.3$, $p < 0.001$). Among the entered variables, education ($\beta = 0.06$, $p < 0.01$), interest ($\beta = 0.28$, $p < 0.001$), and environmental awareness ($\beta = 0.26$, $p < 0.001$) were positively associated with acceptance, i.e., the higher education, interest, and environmental awareness, the higher were acceptance levels. The demographic variables age, gender, income, and subjective knowledge remained to be not relevant, and the residency variables became insignificant in model 3. Among the newly entered attitudinal variables, innovation cautiousness and flight shame were no significant predictors of acceptance.

In **model 4**, the flight frequency as **behavioral factor** was introduced into the model (addressed in RQ5), which resulted in a significant model that explained 18% of the variance (adjusted $R^2 = 0.18$; $F(13, 2047) = 35.1$, $p < 0.001$). No improvement in explained variance was achieved in comparison to model 3 (n.s.), which indicates that flying frequency as an impact factor did not increase the explained variance of CO_2-based fuel acceptance. Among the variables entered, education ($\beta = 0.06$, $p < 0.01$), interest ($\beta = 0.28$, $p < 0.001$), and environmental awareness ($\beta = 0.26$, $p < 0.001$) were positively related to acceptance, i.e., the higher the levels of education, interest and environmental awareness, the higher CO_2-based fuel acceptance. The demographic variables age, gender, income, national residency, subjective knowledge, innovation cautiousness, and flight shame remained to be insignificant in model 4. The newly entered behavioral factor flight frequency was no significant predictor of CO_2-based fuel acceptance.

In **model 5**, risk and benefit perceptions were entered as **evaluations** into the model (addressed in RQ6), which yielded a significant model, that explained 45% of the variance (adjusted $R^2 = 0.45$; $F(16, 2047) = 126.5$, $p < 0.001$). The inclusion of subjective technology perceptions and evaluations led to a 31.6% increase in the explained variance and thus to a significantly improved prediction of CO_2-based fuel acceptance ($F(3, 2031) = 427.2$, $p < 0.001$). Among the entered variables, education ($\beta = 0.05$, $p < 0.01$), interest ($\beta = 0.07$, $p < 0.001$), environmental awareness ($\beta = 0.17$, $p < 0.001$), and flight shame ($\beta = 0.07$, $p < 0.001$) were positively associated with CO_2-based fuel acceptance; Norwegian residency ($\beta = -0.06$, $p < 0.01$) was negatively associated. This indicates that the higher education, interest, environmental awareness, and flight shame were, the higher acceptance levels were reported. Norwegian residents reported lower CO_2-based fuel acceptance levels. The evaluations in terms of benefit and risk perceptions variables, which were newly added to the model, were found to be significant predictors. The strongest predictor was benefit perceptions (β = 0.45, $p < 0.001$), i.e., higher benefit perception levels were related to more positive acceptance levels. Both risk perception dimensions, i.e., health- and environmental risk perceptions (β = −0.12, $p < 0.001$) and perceptions of technical quality and -maturity risks (β = −0.12, $p < 0.001$) were negatively related to CO_2-based fuel acceptance. Thus, the higher risk perceptions were, the lower CO_2-based fuel acceptance ratings. The demographic variables age, gender, income, national residency in Germany and the Netherlands, subjective knowledge, innovation cautiousness, and flying frequency remained to be insignificant in model 5. The variable of Norwegian residency and flight shame became significant as well as the newly entered variables of CO_2-based fuel evaluations.

Summarizing the findings of the hierarchical regression analysis on CO_2-based fuel acceptance, benefit perceptions were by far the strongest predictor, followed by environmental awareness, risk perceptions, interest, flight shame, and Norwegian residency. Respondents with higher benefit perceptions, higher environmental awareness levels, lower risk perceptions regarding health- and environmental risks as well as technical quality and maturity, higher interest and flight shame levels also reported higher acceptance levels. Norwegian residents differed in their ratings from the other European participants and expressed a lower CO_2-based fuel acceptance.

5.2.2 Prediction of the behavioral intention to fly with CO_2-based fuels

When predicting the behavioral intention to fly with CO_2-based fuels (addressed in RQ2), the results of **model 1** revealed that **sociodemographic factors** explained 4% of the variability of CO_2-based fuel acceptance (adjusted R^2 = 0.04; F(7, 2047) = 13.1, $p < 0.001$, Table 4). Among the entered sociodemographic variables, respondents with younger age (β = −0.1, $p < 0.001$), higher levels of education (β = 0.1, $p < 0.001$), and higher income (β = 0.06, $p < 0.05$) reported a higher behavioral usage intention; and residents of Germany (β = −0.08, $p < 0.01$), the Netherlands (β = −0.1, $p < 0.001$) and Norway (β = −0.18, $p < 0.001$) expressed lower behavioral intention to fly with CO_2-based fuels levels. Gender was no significant predictor of the behavioral intention to fly with CO_2-based fuels and the variable Spain was excluded as a predictor in the model.

The inclusion of CO_2-based fuel **awareness** (addressed in RQ3) in **model 2** yielded a statistically significant model (adjusted R^2 = 0.15; F(9, 2047) = 42.1, $p < 0.001$), with a significant improvement in R^2 from 4% to 15% (F(2, 2038) = 137.6, $p < 0.001$). Among the entered variables, age (β = −0.09, $p < 0.001$), gender (β = −0.05, $p < 0.05$), education (β = 0.05, $p < 0.05$), and residency in Norway (β = −0.07, $p < 0.05$) and—as strongest predictor—interest (β = 0.35, $p < 0.001$) exerted predictive utility regarding the behavioral intention to book and fly with CO_2-based fuel. Respondents of younger age, female gender, higher education levels and interest in CO_2-based fuel reported a higher behavioral intention. Residents of Norway reported a lower behavioral intention. The demographic variables income, German and Dutch residency became insignificant as predictors in model 2. The newly entered variable subjective knowledge instead of interest was also not significant.

In **model 3**, the addition of **attitudinal factors** (addressed in RQ4) led to a significant model, that explained 21% of the variance (adjusted R^2 = 0.21; F(12, 2047) = 44.7, $p < 0.001$) and to an improvement in explained variance of 6% (F(3, 2035) = 44.3, $p < 0.001$). Among the entered variables, age (β = −0.08, $p < 0.001$), income (β = 0.06, $p < 0.01$), and—as strongest predictors—interest (β = 0.31, $p < 0.001$) and environmental awareness (β = 0.26, $p < 0.001$) were related to the behavioral usage intention, i.e., respondents with lower age, higher income, interest, and environmental awareness reported higher behavioral usage intentions. The demographic variables gender, education, and residency in Norway became insignificant in model 3, the variables German and Dutch residency and subjective knowledge remained to be insignificant. Among the newly entered attitudinal variables, innovation cautiousness and flight shame were no significant predictors of the behavioral usage intention.

In **model 4**, the flight frequency was entered as a **behavioral factor** into the model (addressed in RQ5), which resulted in a significant model that explained 21% of the variance (adjusted R^2 = 0.18; F(13, 2047) = 42.0, $p < 0.001$). No improvement in explained variance was achieved in comparison to model 3 (n.s.), which suggests that flying frequency as an impact factor did not increase the explained variance of the behavioral usage intention. Among the variables entered, age (β = −0.07, $p < 0.001$), interest (β = 0.3, $p < 0.001$), environmental awareness (β = 0.26, $p < 0.001$), and flying frequency (β = 0.06, $p < 0.01$) had a predictive value for the behavioral intention to book and fly with CO_2-based fuel. Thus, respondents with lower age, higher interest, higher levels of environmental awareness, and a higher flight frequency expressed a higher behavioral intention. The demographic variables gender, education, income, national residency, subjective knowledge, innovation cautiousness, and flight shame remained to be insignificant in model 4. The variable income became insignificant as a predictor in model 4.

Finally, in **model 5**, risk and benefit perceptions were entered as CO_2-based fuel **evaluations** into the model (addressed in RQ6), which resulted in a significant model, that explained 41% of the variance (adjusted R^2 = 0.41; F(16, 2047) = 87.9, $p < 0.001$). The inclusion of subjective technology perceptions and evaluations led to an increase in the explained variance of 20% and thus to a significantly improved prediction of behavioral intention to fly with CO_2-based fuels to fly with CO_2-based fuels (F(3, 2031) = 226.3, $p < 0.001$). Among the entered variables, age (β = −0.09, $p < 0.001$), German residency (β = 0.06, $p < 0.05$), interest (β = 0.14, $p < 0.001$), subjective knowledge (β = 0.05, $p < 0.01$), flight frequency (β = 0.06, $p < 0.01$), benefit perceptions (as strongest predictor) (β = 0.39, $p < 0.001$) as well as risk perceptions, i.e., health- and environmental risk perceptions (β = −0.09, $p < 0.001$) and perceptions of technical quality and -maturity risks (β = −0.12, $p < 0.001$), exerted predictive value in the prediction of the behavioral intention to fly with CO_2-based fuels. Respondents of lower age, German residency, higher interest, and subjective knowledge, higher levels of environmental awareness, higher benefit perceptions, and lower risk perceptions reported higher behavioral intention levels. The demographic variables gender, income, national residency in the

Netherlands or Norway, innovation cautiousness, and flight shame remained to be insignificant in model 5.

Summing up the findings of the hierarchical regression analysis on the behavioral intention to fly with CO_2-based fuels, benefit perceptions were the strongest predictor, followed by environmental awareness, interest, risk perceptions regarding technical quality and -maturity, risk perceptions regarding health- and environmental risks, German residency, flying frequency, and subjective knowledge. This indicates that respondents with higher benefit perceptions, higher environmental awareness levels, higher interest, and lower risk perceptions with regard to technical quality and maturity as well as health- and environmental risks, with German residency, a higher flying frequency, and higher subjective knowledge levels reported a higher behavioral intention to fly with CO_2-based fuels.

6 Discussion

This study investigated the social readiness for using CO_2-based aviation fuels by analyzing the impact of sociodemographic factors, awareness, attitudinal factors, flight behavior as well as evaluations in terms of benefit and risk perceptions on two indicators of social readiness: acceptance and behavioral intention to fly with CO_2-based aviation fuels. The study was run in four European countries to analyze social readiness from a cross-country perspective.

6.1 What drives social readiness of CO_2-based aviation fuels?

Overall, a positively pronounced acceptance and behavioral intention to fly with CO_2-based aviation fuels was observed, which suggests that the CCU production route of alternative fuels meets a positive public resonance and readiness for adoption in the European public. While infrastructure technologies (even in the planning phase) encounter greater skepticism among the public (e.g., Devine-Wright et al., 2017), the willingness to use CO_2-based products such as fuels (Linzenich et al., 2019), but also mattresses (Arning et al., 2018) or insulation boards (Arning et al., 2021) is much more positive.

The analysis of the interconnected effects of impact factors on social readiness revealed that among the *socio-demographic* factors only education was consistently relevant in all models, i.e., with higher education, acceptance of CO_2-based aviation fuels was also higher (H2.3a supported). In contrast, age was the relevant predictor of the behavioral intention in all models, i.e., younger respondents are more likely to fly with CO_2-based fuels (H2.1b supported). The other sociodemographic variables, such as gender and income, were only singularly significant in the models and thus not relevant, i.e., all other hypotheses of research question 2 on the influence of socio-demographic factors were rejected. This is in line with innovation adoption research findings, were younger and more highly educated people express a higher acceptance of sustainable technologies and products (e.g., Tarigan et al., 2012; Bertsch et al., 2016). Overall, sociodemographic variables contributed little (<1%–1.6%) to the prediction of social readiness of CO_2-based fuels (comparable findings are reported by Chen et al., 2020), so that social science adoption research should go beyond these easily measurable but substantively uninformative carrier variables.

In the analysis of the effects of *awareness* of CO_2-based aviation fuels, interest was consistently a (weak) factor influencing acceptance in the models (H3.1a supported); but it exerted a stronger influence on the prediction of the intention to use (H3.1b supported). With higher subjective knowledge, the intention to fly with CO_2-based aviation fuels was also higher (H3.2b supported, the other hypotheses for RQ3 were rejected). Interest and knowledge are known to positively influence the acceptance and adoption of sustainable technologies (Simons et al., 2021a). However, the low level of knowledge about CO_2-based aviation fuels in the sample indicates a) that this topic is too little present in the public and b) the need for carefully planned information and communication about CO_2-based aviation fuels by research and airlines. Otherwise, the risk of misconceptions or misunderstandings—which can lead to negative attitudes—is very high (Slovic, 1987; de Best-Waldhober et al., 2009).

When analyzing the effects of *attitudinal* factors, after controlling for sociodemographic characteristics and awareness, it was found that environmental awareness was the third most important influencing factor overall in the prediction of social readiness (H4.1.a/b supported). When environmental awareness is high, readiness for CO_2-based aviation fuels is also higher, which corresponds to findings of the importance of environmental awareness for the adoption of sustainable innovations (e.g., Linzenich et al., 2019; Todaro et al., 2023). Flight shame was another influencing factor—albeit weakly effective—at least with respect to acceptance in the final model, i.e., higher acceptance of CO_2-based aviation fuels was also reported for higher levels of flight shame. This finding is contrary to the formulated H4.3a and suggests that sustainability values are effective in the perception of flight shame, which also lead to a higher acceptance of CO_2-based aviation fuels (Andersen, 2022). However, flight shame exerted no influence on the actual intention to use CO_2-based aviation fuels (H4.3b rejected). The individual attitude towards innovations was also not relevant for social readiness for CO_2-based aviation fuels, i.e., it cannot be assumed that innovation-minded people, who are more inclined to adopt novel products and technologies, are more likely to accept and want to use CO_2-based fuels as a CCU product.

The inclusion of actual flight frequency as a *behavioral factor* showed that it made no contribution at all to the prediction of acceptance and only a weak contribution regarding the intention to use (H5.1a rejected, H5.1b supported). The finding suggests that frequent flyers cannot automatically be assumed to accept sustainable fuels, but that frequent flying has a positive effect on the intention to fly with CO_2-based fuels.

The most significant factor influencing the readiness for CO_2-based aviation fuels was the subjective *evaluation* of CO_2-based aviation fuels based on risk and benefit perceptions (H6.1a/b and H6.2 a/b supported). With increased risk perceptions regarding environmental and health risks as well as regarding technical quality and maturity of CO_2-based aviation fuels, acceptance and the behavioral intention were lowered (corresponding to Arning et al., 2019; Simons et al., 2021b). As the descriptive analysis showed, risk perceptions were not elevated with respect to environmental and health risks, but there were elevated risk perceptions with respect to product quality and technical maturity of CO_2-based aviation fuels. Since elevated risk perceptions have a negative impact on trust and acceptance, especially among laypersons (Slovic, 1987; Arning et al., 2019), risk communication on CO_2-based aviation fuels should address these concerns and outline that testing procedures and quality requirements are applied to aviation fuels before their usage. The strongest impact factor on social readiness were benefit perceptions regarding CO_2-based fuels, i.e., their contribution to a reduction of CO_2 emissions and to more sustainable air mobility. The strong influence of benefit perceptions on the sociopolitical acceptance of sustainable technologies is consistent with current acceptance models (Huijts et al., 2012; Arning et al., 2020). Communication activities should therefore explicitly address the different benefits of CO_2-based fuels in contributing to a more sustainable mobility.

6.2 National differences in readiness for CO_2-based aviation fuels

In this study, differences in social readiness towards CO_2-based aviation fuels were investigated on an exploratory level. One country consistently differed in ratings from the other countries: Norwegian residents reported a lower interest and subjective knowledge, lower levels of environmental awareness, innovation cautiousness, and flight shame, and the lowest (but still positive) social readiness compared to the other countries. We assume that flying in Norway is a necessity rather than a choice option due to its geographic characteristics. Flying in Norway can be necessary to travel the long distances between cities and to other countries and is therefore less influenced by perceptual evaluations. This assumption is supported by the reported flying frequencies, which was significantly higher for the Norwegian sample than for the other (more centrally located) European countries. However, it must be considered that the survey was conducted during the pandemic and therefore the overall flight frequency was lower. Repeating the study after a normalization of air travel could provide information on the extent to which the results on national differences are reliable and stable and whether there are other, more culturally effective explanatory factors (see section 4.3).

6.3 Methodological considerations and limitations

The present study identified several empirical, conceptual, and methodological issues that need to be considered to achieve a holistic picture of CO_2-based aviation fuel readiness.

6.3.1 Measurement of social readiness

In this study, social readiness was operationalized by ratings of acceptance (as attitude) and behavioral intention (as approximation to behavior). The "attitude-behavior-gap" (e.g., ElHaffar et al., 2020) suggests that attitude and intended or actual behavior might differ. The results showed that 1) acceptance ratings were more positive than the behavioral intention to fly with CO_2-based fuels, which indicates there is a risk of overestimation of social readiness if research is limited to acceptance measures, and 2) that social readiness is shaped by different impact factors than acceptance. In contrast to acceptance, the behavioral intention was influenced by age (which might reflect financial capabilities), to a greater extent by interest, and by actual flight frequency, whereas factors influencing acceptance, such as education or flight shame, did not play a role. Social science research on the readiness to adopt sustainable innovations should therefore always cover both indicator levels to make its findings more predictive, accurate, and valid.

Overall, however, it must be considered that the proportion of variance explained for social readiness in both hierarchical regression models was 45% (for acceptance) and 40% (for behavioral intention). This means that social readiness is also influenced by other factors that were not measured in this study. Although the proportion of variance explained is often even lower for social science regression studies (e.g., Lienert et al., 2015; Chen et al., 2020), additional influential factors (e.g., social norms or values) should be identified and included in future regression modeling.

An important aspect in relation to social readiness is the price or willingness to pay, which was not included in this study. Costs are a very influential and dominant criterion in studies on the perception of technology and product innovations, which can obscure the differentiated analysis of other relevant influencing factors in stated preference analyses (e.g., Linzenich et al., 2019). Moreover, presenting realistic prices on CO_2-based fuels in surveys is currently not feasible, as CO_2-based fuels are not yet on the market and price estimates vary widely. Unlike in the case of cars, the price of aviation fuel is typically not a tangible factor for consumers. Thus, it is worthwhile to explore the tradeoffs between benefits to combat climate change *versus* potential higher costs at a later stage when the products are available in the market in future studies.

6.3.2 The role of national differences

In this study we did not only investigate social readiness for CO_2-based aviation fuels for one single country, but analyzed differences between South, North, West, and Central Europe. The specific countries were chosen due to the research interest of the eCOCO$_2$ project consortium. With the findings described above, it is important to keep in mind that the readiness for CO_2-based aviation fuels in each country is impacted by a multitude of variables, which are carried by nationality. This means that differences between nationalities are not caused by participants having a different nationality as such, but rather by other cultural and behavioral differences between nationalities. In this paper, we surveyed a reasonable number of sociodemographic, attitudinal, and behavioral variables as well as evaluations in terms of benefit- and risk perceptions in each country. To achieve a more conclusive picture on national differences further studies should include culture-sensitive explanatory variables and integrate socioeconomic differences and macro-level factors, e.g., gross domestic product (GDP), human development index (HDI) growth, or sustainability indices, but also policy settings to include the countries' strategies to politically foster openness to sustainable technologies.

6.3.3 The role of flight shame

In this study flight shame was integrated as it was unclear how it might be related to the social readiness for CO_2-based aviation fuels. Increasingly, research addresses the concept (Chiambaretto et al., 2021; Andersen, 2022; Gunziger et al., 2022) and it becomes clear that the concept of flight shame might target at very different social phenomena, starting from the increasing awareness of flight passengers that flying with fossil fuels is contributing to climate change. It also represents a moral argument in the sense of a moral responsibility that is used by climate opponents, journalists, or industrial stakeholders to announce a pro- and a contra-argumentation for as well as against flying. In future studies, the concept of flight shame should be theoretically and methodologically elaborated to understand the relationship between flight shame, acceptance, and sustainable behavior. Also, it should be monitored whether the willingness to forego flights is more than just a one-day fly-by used in the media or a serious change in the mental attitude of consumers towards a thoughtful and sustainable use of resources.

6.3.4 The impact of temporal context and crises

Data collection took place in a specific temporal context, namely, in the first year of the COVID 19-pandemic, when the awareness and value of free mobility increased due to worldwide travel restrictions (e.g., Nicola et al., 2020). Another strong influencing factor was the discussion about climate change and the necessity to reduce global CO_2 emissions, also by defossilizing the transport sector. People's experiences throughout such global developments may seriously alter perceptions, attitudes, and priorities. The strong dependency on fossil energy could alter the public perception in different ways. It is possible that the development of CCU technologies and of CO_2-based products receives increased support, due to the strong priority of climate change mitigation measures. Also, the fear of job loss in a fossil aviation industry could be altered by the fact that novel and decarbonized fuels create novel job opportunities. However, it could also change the public perception in the opposite direction. In times of energy shortages and increasing prices, a rearrangement of priorities regarding energy-intensive processes such as the conversion of CO_2 is conceivable. Further, it can be assumed that the war in Ukraine and the resulting energy crisis in Europe could also influence the perception of CCU and products. Another aspect that should be taken into account is the general low public awareness of the CCU technology and of the various products that can be launched with his technology (Perdan et al., 2017; Offermann-van Heek et al., 2018; Arning et al., 2019). Whenever more CCU products are marketable and consumers can get into direct contact with the novel products, the awareness for and acceptance of CO_2-based products could also change. Thus, future studies should replicate the findings and monitor public perceptions to reflect these temporal-context-related changes.

In conclusion, the study found a positive public readiness for the adoption of CO_2-based aviation fuels in the European public. The sociodemographic factors contributed little to the prediction of social readiness, with only education and age being consistently relevant predictors. Awareness, interest, and knowledge were found to positively influence social readiness, with the need for carefully planned information and communication about CO_2-based aviation fuels. Environmental awareness and flight shame were found to be important influencing factors on social readiness. The subjective evaluation of CO_2-based aviation fuels based on risk and benefit perceptions was found to be the most significant factor influencing the readiness for adoption. Overall, the study highlights the importance of understanding the complex interplay of factors influencing social readiness and the need for carefully planned communication and information campaigns to support the adoption of sustainable technologies.

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by the Ethics committee of RWTH Aachen University. The participants provided their written informed consent to participate in this study.

Author contributions

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

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2023.1156709/full#supplementary-material

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