Linzenich *et al.*
Energy, Sustainability and Society (2023) 13:35
https://doi.org/10.1186/s13705-023-00412-5

Energy, Sustainability and Society

RESEARCH Open Access

What's in my fuel tank? Insights into beliefs and preferences for e-fuels and biofuels

Anika Linzenich[1*], Dominik Bongartz[2,3], Katrin Arning[4] and Martina Ziefle[1]

Abstract

Background Alternative fuels made from biomass or CO_2 and water using renewable energy can reduce CO_2 and pollutant emissions compared to fossil-based mobility and thus support a transition to a more sustainable transport. The adoption of alternative fuels in transport will ultimately depend on public acceptance and drivers' willingness to use them. Little is known if and under which circumstances people would accept alternative fuels and which narratives and cognitive beliefs might underlie these usage intentions. Moreover, it is unclear if and how laypeople distinguish between different alternative fuel types in their perceptions, e.g., between fuels made from biomass (biofuels) and fuels produced using electricity (e-fuels). To address the research gap, this study empirically investigated laypeople's beliefs and expectations towards alternative fuels and preferences for different fuel types. Understanding preferences for fuel types could help in steering public information, support managerial decisions and communication pathways, and promote the roll-out process of fuel innovations.

Results Laypeople expected alternative fuels to be made using renewable feedstocks and to not contain gasoline or diesel. Whereas alternative fuels were believed to have advantages concerning environmental and toxic effects and safety compared to diesel and gasoline, they were associated with practical disadvantages for drivers. It was shown that although e-fuels and biofuels both fall under the definition of "alternative fuels", laypeople distinguish between them in evaluations of safety, costs, and resource competitiveness: E-fuels were preferred over biofuels and believed to have a lower competition for resources than biofuels. They were also evaluated to be more expensive and comparably less safe to use. Moreover, different adopter groups were identified for both fuels.

Conclusions The study has highlighted both adoption drivers and barriers for alternative fuels: Reduced environmental impact could be an important positive factor. In contrast, drawbacks feared by laypeople regarding a low range and an expensive fuel price could be barriers for alternative fuel adoption because they reflect current technical challenges for these fuels. Thus, a more cost-efficient production and higher fuel efficiency should be considered in an acceptance-optimized alternative fuel production.

Keywords Social acceptance, Public perceptions, Beliefs, Fuel preferences, E-fuels, Biofuels

*Correspondence:
Anika Linzenich
linzenich@comm.rwth-aachen.de
Full list of author information is available at the end of the article

Background

The mobility sector faces serious global challenges: On the one hand, mobility is an essential part of human life because it connects different areas of life such as home, job, and recreational activities [1, 2] and allows social participation. On the other hand, fossil automobility today is one of the largest emitters of CO_2 and pollutant emissions [3]. Thus, mobility has to become more sustainable while becoming more affordable and has to be accepted by the public to be successfully implemented [4].

One option of transforming mobility is the use of alternative fuels. Even if zero-emission passenger cars will only be allowed to be registered in the EU from 2035 onwards, the vehicles with internal combustion engines still need fuel. To increase sustainability in this vehicle fleet and to reduce CO_2 emissions, alternative fuels remain an important research topic, especially on the global level.

The acceptance of alternative fuels requires people's recognition and understanding of the novelty and advantageousness of a technical innovation. It also involves that they adopt the innovation, value the advantageousness more than any perceived risks or drawbacks, and ultimately accept the novel technical product. [5, 6]. Especially when it comes to a product that people are somewhat familiar with, as is the case with traditional fuels for vehicles, it is essential to ensure that laypeople properly understand the novel product, i.e., the "alternative fuels". This is important to prevent the intuitive transfer of properties of the well-known product to the novel product although this does not necessarily match in all cases (see, e.g., [7–9] for cognitive biases and inference errors, [10] for misconceptions transferred from the CCS context to the CCU context, and [11] for mental models of energy storage). False assumptions that stem from other usage contexts along with lower technical domain knowledge bear the risk that the cognitive beliefs and misconceptions of the public lead to a premature rejection of the product, as was the case in Germany with E10 [12].

From a social science point of view, the knowledge about human decision-making and cognitive beliefs about the innovation has different advantages: First, public perceptions and expectations towards fuel innovations can be integrated into technological design. Second, they serve as a basis to accompany the market launch with tailored information and communication strategies; and third, policy makers can profit from the knowledge about public attitudes to steer policy actions and political communication.

From a technical point of view, integrating acceptance investigation into the development of alternative fuels can be beneficial in two respects: It can avoid wasting development effort on fuel candidates that are likely to be rejected by the public or future users. Also, it can provide guidance for weighing the relative importance of the numerous performance metrics that can be used to assess alternative fuels.

Yet, there is little to no knowledge about these public presumptions in the context of alternative fuels for automobility.

It is thus a timely research duty to assess what laypeople—which are the people who have to accept alternative fuels in the end—mean by the term "alternative fuels". Since the ideas and beliefs that people hold can shape expectations towards new fuel types and determine the readiness to adopt fuel innovations [11], it is crucial to gain insights into how laypeople imagine an alternative fuel. Knowledge about this helps to inform about the expectations and requirements for alternative fuels and to uncover possible misconceptions which can be addressed by transparent and tailored information concepts. The second novelty of the research approach is the comparison of perceptions for different fuel types (biofuels vs. e-fuels). To the best of our knowledge, no study so far has compared perceptions of e-fuels and biofuels in one frame of reference. Since fuel options do not exist in isolation but always in the context of other fuel choice options, it is important to understand how biofuels are perceived compared to e-fuels and which of the fuel types is more preferred to understand their future potential for adoption by drivers. To close these research gaps, the paper addresses the following research aims:

1. The revelation of lay beliefs and expectations about alternative fuels.
2. The comparison of lay perceptions regarding different fuel types (biofuels vs. e-fuels).

Technical background: alternative fuels for sustainable mobility

The term "alternative fuels" can refer to any fuels other than those in wide use today. It can thus refer to fuels for different applications including passenger vehicles, trucks, trains, ships, or airplanes, as well as for different propulsion systems. Some existing definitions even include electricity for use in battery electric vehicles. In this contribution, we focus on combustion engine fuels for vehicle applications only, and thus alternatives to gasoline and diesel fuel.

The large variety of potential alternative fuels for this application can be categorized by the main energy source used in their production: The main energy input can come from fossil sources (e.g., for liquified petroleum gas

(LPG) or compressed natural gas (CNG)), from biomass (in case of biofuels), from renewable electricity (in case of e-fuels), or directly from sunlight (in case of solar fuels). Among these categories, we focus on biofuels and e-fuels in the following.

Biofuel production

For biofuels, biomass is both the material feedstock and the main energy source. There is a broad variety of biofuels in terms of their chemical composition, their production processes, and their required biomass types used as feedstock. The production processes can be broadly categorized as either thermochemical, where the main conversion steps are high-temperature chemical reactions, or biochemical, where the main conversion steps are facilitated by microorganisms and/or enzymes [13].

In terms of feedstock, the majority of the biofuel production today relies on plants that are rich in sugars or fatty oils. Examples include bio-ethanol produced from, e.g., corn or sugar cane, or bio-diesel produced from, e.g., soy or rapeseed. The production of these biofuels has caused controversy due to the competition with food production since it is either directly based on food crop or uses arable land that could also be used for food production [14].

Recent efforts have been focused on biofuels that can be produced from feedstock that do not compete with food production [14]. This includes biofuels produced from lignocellulosic biomass such as wood or by-products or residues from other agricultural processes (e.g., straw). Another option are biofuels produced from algae, which have higher growth rates and require less land, but need more fresh water and nutrients. Finally, some potential biofuels rely on genetically modified microorganisms. The actual fuels produced from such feedstock can be the same as some more conventional biofuels (e.g., ethanol production from lignocellulosic biomass instead of corn [14]), or new ones, potentially even optimized fuel blends for a given engine type [15].

E-fuel production

For e-fuels (also called electricity-based fuels or electrofuels), the main energy input is electricity. As first step in the production of e-fuels, this electricity is typically used to produce H_2 via water electrolysis. This H_2 can be used as a fuel itself in fuel cell vehicles or in combustion engines, or it can be further reacted to produce other fuels.

To convert the H_2 to a hydrocarbon or oxygenated fuel, it needs to be combined with a carbon source. The most common carbon source proposed in literature is CO_2, the resulting fuels including, for example, methane [16], methanol [17], Fischer–Tropsch gasoline or diesel (either directly [18] or via methanol [17]), or oxymethylene ethers [3]. In this case, the production processes also constitute carbon capture and utilization processes, and the corresponding fuels are sometimes also called CO_2 -based fuels. The required CO_2 can come from power plants, industrial or bio-based processes, or be directly captured from air. While there will likely be sufficient amounts of CO_2 available, obtaining CO_2 from these different sources entails different environmental impacts and in particular different greenhouse gas emissions, mainly because of the different energy demands for CO_2 separation [19]. Furthermore, the environmental impact and availability of these CO_2 sources may change in the future.

Properties of biofuels and e-fuels compared to diesel and gasoline

It is difficult to universally characterize the properties of biofuels and e-fuels since both come in a variety of forms: They can be pure chemical species, e.g., in the case of bio-ethanol or e-methanol, or they can be mixtures of many species, e.g., in the case of bio-diesel or e-Fischer–Tropsch gasoline or diesel. They can be stored and used as a gas, e.g., methane (which can be a biofuel in case it is derived from biogas, or an e-fuel if it is produced from H_2 and CO_2), or as a liquid, e.g., bio-ethanol or e-methanol. Furthermore, they can either be neat fuels (i.e., used by themselves without other fuels), or blend components to be combined with other fuels, as is currently often done for bio-ethanol or bio-diesel, or may even be required for some fuels such as oxymethylene ether (also known as OME_1) [20].

Similarly, the performance of biofuels and e-fuels in vehicle applications differs widely depending on the exact fuel (cf., e.g., [21] for a comparison of e-fuels). However, many alternative fuels exhibit a lower energy density than gasoline or diesel since they have a high oxygen content (e.g., methanol) and/or are a gas and thus have a lower volumetric mass density (e.g., CNG). If such compounds are used as neat fuels or as significant fractions of fuel blends, this lower energy density may translate into reduced driving range. Furthermore, most fuels require adaptions to be usable in existing engines, or even require new engines altogether (cf., e.g., [22] for the case of oxymethylene ethers). However, there are several biofuel or e-fuel candidates that enable lower formation of pollutants such as carbon monoxide, particulates, or NO_x. An example that has received significant attention recently are oxymethylene ethers which enable dramatic reductions in pollutant formation even when blended with fossil diesel [20]. In contrast, some alternative fuels can also cause increased formation of certain types of pollutants, e.g., smaller particulate matter [23].

Reducing greenhouse gas emissions is a main motivation for the development of biofuels and e-fuels. For e-fuels, it is widely known that electricity must have a low carbon footprint for such fuels to provide benefits over fossil fuels in terms of greenhouse gas emissions. In some countries, e-fuels can have lower greenhouse gas emissions than fossil fuels already when using today's electricity mix, while in other countries significant expansion of low-carbon electricity sources is still required [3]. The correct evaluation of life cycle greenhouse gas emissions has been subject to some controversy for CO_2-based production pathways. However, these can be resolved with strict application of existing standardized procedures [19], and such pathways can in fact be environmentally beneficial. For biofuels, there has also been some controversy, including the effect of land use change. However, recent studies conclude that biofuels also enable reduced greenhouse gas emissions [13]. Direct comparisons between biofuels and e-fuels are difficult because the exact values of emissions are heavily dependent on the details of the production processes and the raw material and energy supply. However, e-fuel production typically enables more efficient utilization of the carbon contained in the feedstock, which may contribute to lower greenhouse gas emissions [24].

Beyond greenhouse gas emissions, other performance criteria, including fuel cost, water use, and land requirement, are also dependent on the production pathways and raw material and energy supply. Fuel production costs tend to be higher for e-fuels than for biofuels, mainly because of high costs for renewable electricity and the water electrolyzer [25]. In contrast, e-fuels require significantly less water than biofuels [26]: While for e-fuel production, water is mainly required for electrolysis, many biofuel pathways require large amounts of water for biomass production [13]. Similarly, the land requirement is also expected to be lower for e-fuels than for biofuels [26]. Additionally, the land requirement for e-fuels mainly exists because of the renewable electricity production which is not limited to arable land, or may admit other simultaneous uses (e.g., for agriculture or fishing in case of wind power).

Social science background: acceptance of fuel innovations

Public perceptions and beliefs of alternative fuels

Studies dealing with the acceptance and general perceptions of the concept "alternative fuels" as such are rare (an exception includes [27], where preferences for alternative fuels were examined). Past research concentrated mainly on preferences for alternative fuel vehicles (AFVs), e.g., [28, 29]. However, the focus on *vehicles* (AFVs) lacks the representation of mental concepts of laypeople about "alternative fuels" as energy carrier because of two reasons: First, insights into the evaluation of the fuel itself cannot be derived on the basis of results on AFVs as the evaluation of AFVs is always a combination of the new propulsion technology and the new vehicle that has to be bought or rented. This combination cannot be easily broken down into evaluation parts for the fuel and the car. The second factor blurring perceptions of alternative fuels is that in acceptance studies, the term AFV is often not limited to fuels used in combustion engines but is used in a wider sense for different alternative propulsion technologies including battery and hybrid electric vehicles (e.g., [30, 31]). Therefore, it is currently unclear what laypeople understand about the term "alternative fuels" and how they imagine an alternative fuel to be with regard to its production and usage.

Several studies have dealt with public perceptions and acceptance of specific fuel types. Most of them have looked into public perceptions of biofuels (e.g., [32–34]) but only few studies have examined the acceptance of e-fuels in road transport and aviation (e.g., [35, 36]).

Acceptance of biofuels

For biofuels, perceived benefits outweighed the perceived risks. In turn, benefits were revealed to impact the attitude towards biofuels [37]. In acceptance research on biofuels environmental, health-related, economic, and usage-related factors were identified as acceptance-relevant.

A recent study [32] identified *advantages for human health and the environment* as well as *economic advantages* for farmers growing biofuel feedstocks as main usage motives for biofuels. Likewise, previous research revealed a positive effect of the perception of environmental benefits on biofuel acceptance [38]: People who believed that fossil fuels contribute to climate change, that less use of fossil fuels has relevant environmental benefits, and that biofuel production has no relevant negative consequences for biotopes and biodiversity were found to be more willing to use biofuels. Furthermore, it was revealed that people who believed biofuels to have advantages for the environment in the form of providing a means against climate change and who did not expect negative consequences for the air and water quality due to biofuel feedstock production were willing to even pay a higher price for biofuels [38].

Still, in other studies (e.g., [39]) positive environmental effects were not seen by drivers: Biofuels were not believed to have a cleaner combustion than gasoline. However, this statement was presented together with the statement that biofuels had no contribution to greenhouse gas emissions. Thus, it is not clear whether the disagreement about these statements means that respondents believed biofuels to not be cleaner in their combustion than conventional fuels or whether they thought that biofuels burn cleaner but still contribute to GHG emissions.

It was also reported that biofuels and their production are linked with *environmental and ethical concerns*: A perceived trade-off and concern was identified between biofuel and food production [34], e.g., in the form of higher food prices [40, 41]. Higher food prices and food supply insecurities can lead to rejection of biofuel development [42]. Concerns about increased food prices do not only apply to biofuels produced directly from edible feedstocks but can also affect support for second generation biofuels [43], e.g., due to a perceived competition for land use between the production of crops for food and biofuel feedstocks. As such, agricultural waste was identified as preferred feedstock for biofuels compared to edible crops [34, 44]. Instead, Savvanidou et al. [38] showed that people who do not believe that the production of biofuels leads to higher food prices have a higher willingness to use biofuels. For biofuel feedstock preferences it was also revealed that plants which are not genetically modified were more approved than GM biomass [45].

With regard to environmental and health-related perceptions, health-related aspects were rated higher than environmental effects: people would be more willing to pay a higher biofuel price for reducing human health risk rather than reducing resource consumption and negative environmental effects [46].

The importance of *fuel-usage-related factors*, e.g., availability and price, has been emphasized [45]: The willingness to buy biofuels was positively influenced by the *provision of sufficient information* about biofuels and the *availability* of biofuels at fuel stations [32]. More people were ready to refuel biofuels if these were as available as fuel stations for diesel [33]. Fuel price was identified as an obstacle for biofuel acceptance (e.g., [47]) showing that more people were willing to use biofuels if they cost the same as diesel compared to a higher price [33]. Next to fuel price, whether the biofuel is compatible with one's car and whether its use has negative impacts on the engine plays an important role [45].

However, for different user groups different usage motives for biofuels matter, e.g., related to environmental effects, social effects, and the required effort to use biofuels [47]. Likewise, for drivers of passenger vehicles biofuel characteristics such as price and performance matter most, whereas for freight vehicle drivers biofuel availability and policies play a special role [48].

Studies on biofuel acceptance have also examined the effects of user diversity. In some studies, an effect of sociodemographic factors was revealed. A younger age, a female gender, and a higher income were associated with a more positive perception of biofuels [33, 49]. Moreover, people with a higher education were willing to pay higher prices for biofuels than people with a lower education [38]. Contrary to this, however, in another study [50] a higher formal education was linked to biofuel use being perceived more negatively.

Environmental concerns impact both the beliefs about biofuels and the intention to use and pay for biofuels [51]. Additionally, a more positive environmental self-identity was linked to a higher willingness to use biofuels [33]. Mixed results were found for the impact of domain knowledge on biofuel perceptions. Some studies (e.g., [49, 52]) found a negative effect of factual knowledge on perceptions: People with more knowledge about biofuels perceived a less positive benefit–risk balance, i.e., less advantages in relation to risks, than people with less knowledge [49]. Furthermore, people with more self-assessed knowledge about biofuels showed a lower willingness to pay for biofuels [52]. In contrast, other studies revealed higher factual knowledge and self-reported knowledge about biofuels to be linked to more willingness to use biofuels [33, 51].

Acceptance of e-fuels

Previous research on CO_2-based fuels has examined risk perceptions of CO_2-based fuels with regard to toxic effects [35] and the impact of perceived benefits and barriers of CO_2-based fuels on their acceptance in aviation [53]. Furthermore, preferences for CO_2-based fuels and their production were investigated and how technically accurate information on environmental effects influenced these preferences [36, 54]. Risk perceptions and factors perceived to cause toxic effects were significantly lower for CO_2-based than conventional fuels [35]. Moreover, the acceptance of CO_2-based fuels as end-product was higher than the acceptance of their production process [36]. In the context of aviation, the acceptance of CO_2-based fuels was directly impacted by perceptions of benefits and barriers of the fuel and (mostly) indirectly by perceptions of the production process of using CO_2 as a feedstock [53].

Like in the context of biofuels, for CO_2-based fuels diverging requirements were found for different user groups with some consumers being more oriented towards environmental performance and others paying more attention to financial criteria [54].

Still, no study to date has directly compared perceptions of e-fuels and biofuels. Thus, it is not understood which fuel type is more preferred from laypeople perspective and if and how perceptions of the two fuel types differ from each other.

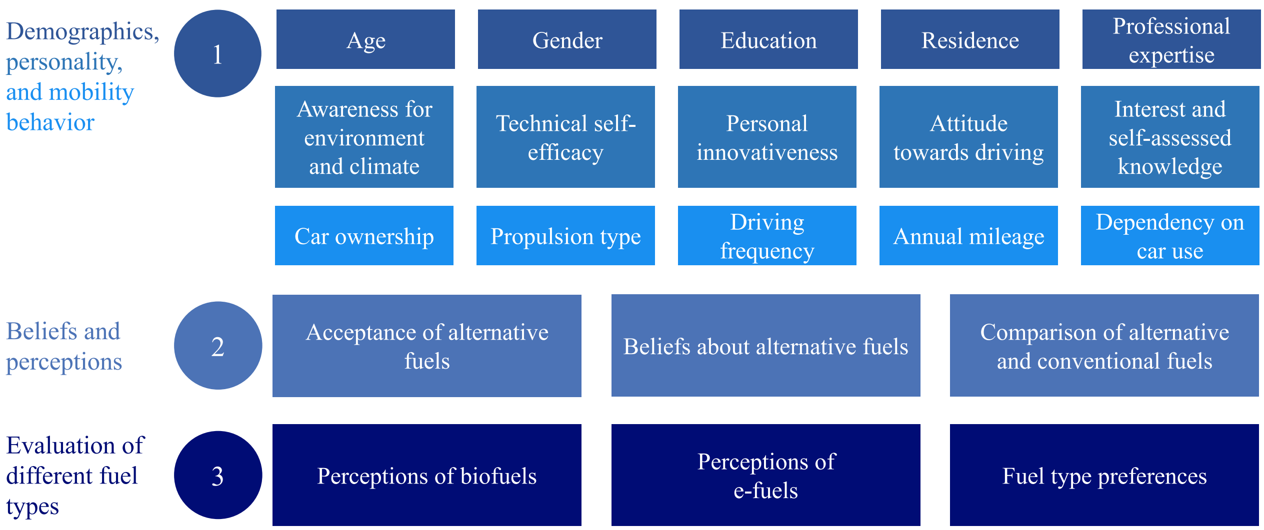

Fig. 1 Questionnaire structure

Addressed research gap

The summary of the state of research has highlighted two research gaps:

1. *Laypeople's understanding of alternative fuels:* It is currently unclear what laypeople understand by the term "alternative fuel" and how they imagine an alternative fuel to be. These images and beliefs can shape expectations towards alternative fuels and thus the readiness to use these new fuel types. Therefore, it is important to understand laypeople's mental concepts of alternative fuels to identify the requirements that they hold towards alternative fuels which in turn can be considered in fuel design. This also helps to uncover possible misconceptions, e.g., related to feared drawbacks or unrealistically high expectations that are not met by the technical reality.

2. *Comparison of different fuel types:* So far, no study has compared perceptions of e-fuels and biofuels in one frame of reference. Since fuel options do not exist in isolation but always in the context of other choice options, it is important to understand how biofuels are perceived compared to e-fuels and which of the fuel types is preferred the most.

To address the two research gaps, the paper looks into the following research questions:[1]

1 Which beliefs and expectations do laypeople hold about alternative fuels (how do laypeople "imagine" an alternative fuel)?
2 How do laypeople evaluate different fuel types (biofuels vs. e-fuels)?

Methods

To investigate the beliefs about alternative fuels and perceptions of different fuel types, an online survey was conducted in Germany in early 2021. In the following, the questionnaire used, the survey sample, and the data analysis will be described.

The questionnaire used in the survey included three parts (see Fig. 1). An overview of the constructs and items from the questionnaire is given in Table 5 in the Appendix (see also Figs. 2, 3, 4, 5).

At the beginning of the questionnaire, participants were briefly introduced to the topic of alternative fuels.

The first part addressed the sample's demographic and personality characteristics and driving behaviors. As demographic factors, age, gender, education, residence, and professional expertise in fuel and engine research were assessed. The considered personality characteristics were attitudes towards environment, technology, and driving as well as interest in alternative fuels.

Awareness of environment and climate change was measured with six items (Cronbach's alpha = 0.85, item sources: [55–57]) adapted to the context of fuel-based mobility. Additionally, the perceived individual responsibility for contributing to environmental problems via one's mobility behavior was assessed with two items (Cronbach's alpha = 0.46) based on previous research [58] adapted to the context of fuel-based mobility.

[1] Since the study explores very new research topics (mental concepts of alternative fuels and e-fuel vs. biofuel preferences) about which little is known so far, the study did not aim at a representative sample size, which would be required for confirmation and generalization of already tested theoretical acceptance models. Instead, the goal was to identify and understand acceptance-relevant factors and to make acceptance requirements visible, for which the targeted survey sample was sufficient.

The general attitude towards technology was assessed in terms of technical self-efficacy (four items, Cronbach's alpha = 0.90, item source: [59]) and personal innovativeness (four items, Cronbach's alpha = 0.88, item source: [60]). Whereas the technical self-efficacy captures the personal affinity towards technology and the self-confidence in interacting with technology, the personal innovativeness relates to the openness and interest towards innovative technologies.

To assess the role that driving played for the sample (necessary action or symbol of fun and reputation), the attitude towards driving was measured with seven items (Cronbach's alpha = 0.82, item source: [61]).

To control for interest and awareness regarding the survey topic, one item measured the interest in alternative fuels while self-assessed knowledge about alternative fuels and their production was measured by two items (Cronbach's alpha = 0.90, item source: [35]). All attitudinal variables were measured on six-point Likert scales.

As indicators for the driving behavior of participants, car ownership, propulsion type, driving frequency (before and during the COVID-19 pandemic), annual mileage, and the self-assessed dependency on car use were included.

The second part captured perceptions of alternative fuels in general. Acceptance of alternative fuels was measured with four items (Cronbach's alpha = 0.75, item source: [35]) on the attitude towards and the willingness to use alternative fuels to be answered on a six-point Likert scale. Moreover, beliefs about alternative fuels were assessed using a semantic differential [62] consisting of six bipolar scales related to fuel properties (feedstocks used and state of matter) and consequences for fuel usage. The semantic differential technique was not only used in its original sense to capture predominantly affective reactions but was applied to avoid bias of respondents by the use of one-directional statements. A semantic differential was also used to identify perceived strengths and weaknesses of alternative compared to conventional fuels (diesel and gasoline) and thus to uncover possible enablers and inhibitors of the adoption of alternative fuels. Ten bipolar scales compared alternative fuels to diesel and gasoline in terms of environmental effects, risks, and fuel usage. Both semantic differentials had 5-point-answering scales.

The third part of the questionnaire focused on perceptions of different fuel types (biofuels vs. e-fuels). In the beginning, the two fuel types were introduced by an infographic visualizing the production of biofuels and e-fuels. Respondents were then asked to rate biofuels and e-fuels on a five-point semantic differential regarding benefits, costs, risks, and environmental effects. The survey closed with a question on fuel type preferences. Participants were asked to indicate whether they would prefer biofuels or e-fuels given the same fuel costs, whether they had an equal preference for both fuel types, or whether they would rather choose none of the fuels.

The evaluative dimensions of the semantic differentials used were derived from previous interview studies conducted prior to this research. The questionnaire was pre-tested by laypeople to ensure the clarity and comprehensibility of the questions and instructions.

Survey sample

254 respondents participated in the study, after a quality control (excluding incomplete and inconsistent answering patterns) 208 data sets remained for further analysis (response rate: 81.9%). It was convenience sampling with the survey link being distributed via e-mail and social media. Participants were selected based on their interest for alternative fuels and through personal networks. The 208 respondents were between 18 and 80 years old ($M =$ 34.4 years, SD = 13.8) with 46.2% females and 53.4% males (0.5% made no indication on their gender). Asked for their highest formal educational achievement, 59.6% of respondents reported a university degree or Ph.D., 37.0% a high school degree or completed vocational training, and 3.4% had completed primary, secondary, or middle school. 15.4% of the participants reported that their education or job was in the field of fuel development or combustion engines. Thus, the large majority of the sample (84.6%) were laypeople with regard to fuel and combustion engine research. Most respondents lived in an urban area (48.1% in the city center, 36.1% in a suburb or in the city outskirts), while 15.9% resided in the countryside.

The sample reported high awareness for environment and climate change ($M = 4.73, \mathrm{SD} = 0.83$) and relatively high perceived responsibility of their own mobility behavior for the current environmental problems ($M = 3.96, \mathrm{SD} = 1.01$). Also, the technical self-efficacy (as indicator for the general attitude towards technology) was rather high ($M = 4.07, \mathrm{SD} = 1.28$) but the personal innovativeness was moderate ($M = 3.48, \mathrm{SD} = 1.16$, $n = 207$). There was a high interest in alternative fuels ($M = 4.43, \mathrm{SD} = 1.13$) and a high acceptance of alternative fuels ($M = 5.07, \mathrm{SD} = 0.75$) but the self-assessed knowledge about alternative fuels was rather low ($M = 2.84, \mathrm{SD} = 1.22$).

The driving behavior of the sample is summarized in Table 1. Most respondents had access to a car and used conventional fuels in their primarily used vehicle.[2] Half of the sample (49.5%) felt dependent on car use in their

[2] We asked here for the propulsion type of the primarily used vehicle, not specified to cars. This may explain why although $n = 23$ participants reported not to have access to a car, $n = 201$ respondents answered the question on vehicle propulsion type.

Table 1 Driving behavior of the sample ($n = 208$)

Driving behavior	Percentage
Car ownership	58.2% have own car, 27.9% use car of family/friends, 5.3% use company car, 7.2% use carsharing or rented car, 11.1% have no access to car
Vehicle propulsion type ($n = 201$)	68.7% gasoline, 23.4% diesel, 2.5% EV, 2.0% hybrid, 0.5% gas, 3.0% other
Car dependency	$M = 3.43$ (SD = 1.80)
Driving frequency (before COVID-19)	8.7% never, 22.6% several times / year, 13.9% several times / month, 27.9% several times / week, 26.9% daily
Annual mileage	10.6% prefer not to say/ don't know, 53.4% up to 10,000 km, 24.0% >10,000–20,000 km, 12.0% > 20,000 km

everyday life (fully-rather agree). The sample was also asked to indicate their attitude towards driving, which was rather negative ($M = 2.71, \mathrm{SD} = 0.94$), meaning that driving was rather seen as necessary and less as a pleasure or status symbol.

Data analysis

Results were analyzed using descriptive and inferential statistics. Mean values were calculated for all scales with multi-item measurements. To analyze mental concepts and beliefs of alternative fuels, mean values were calculated for the evaluative dimensions in the semantic differential. t-Tests were used to test for statistically significant deviations of the mean values from the scale midpoint (= 3). The same procedure was applied to analyze evaluations of alternative fuels compared to conventional diesel and gasoline.

Differences in the perception of different fuel types (biofuels vs. e-fuels) were examined by one-way repeated-measures ANOVAs.[3] A MANOVA was conducted to investigate whether people with a preference of different fuel types differed in their perceptions of biofuels and e-fuels. Furthermore, demographic and personality profiles of the fuel preference groups were examined by ANOVAs.

Results

Insights into lay beliefs: what makes a fuel "alternative"?

Beliefs about alternative fuels were assessed on a semantic differential relating to properties of the fuels and their production. Results are visualized in Fig. 2. Like Fig. 2 shows, alternative fuels were expected to be made of renewable feedstocks, to not contain conventional gasoline and diesel, and to be incompatible with conventional vehicles. For these three evaluative dimensions, mean values deviated significantly from the scale midpoint (see Table 2).[4]

In contrast, no significant deviations from the midpoint were found for the energy used in the production, the state of matter of alternative fuels, and fuel usage. This means that the sample was undecided (meaning heterogeneous in their evaluation) whether renewable energy or an energy mix would be used for producing alternative fuels, whether the new fuels would be gaseous or liquid, and whether they would differ in usage compared to conventional fuels.

Expectations towards alternative fuels compared to diesel and gasoline

To identify possible enablers and inhibitors of alternative fuel adoption, it was investigated how alternative fuels are evaluated compared to conventional fuels (diesel and gasoline). Figure 3 shows that alternative fuels were perceived to have significantly less environmental effects than diesel and gasoline since they were perceived to have a cleaner combustion and a lower CO_2 footprint, to be more sustainable, and to produce less pollutant emissions. All mean values had a significant difference from the scale midpoint (3) (see Table 3).[5] Only the expected land use did not differ significantly between alternative and conventional fuels (no significant difference from the scale midpoint).

Regarding perceived risks, alternative fuels were perceived as significantly safer to use and to have fewer toxic effects than diesel and gasoline (see Table 3).

Whereas alternative fuels were evaluated as advantageous in environmental effects and safety, they were associated with drawbacks regarding their use: Alternative fuels were perceived as more expensive and to decrease the driving range compared to diesel and gasoline. Both mean values differed significantly from the scale midpoint (see Table 3). However, alternative fuels were not perceived as significantly more difficult to use than conventional fuels.

[3] ANOVA = analysis of variance, MANOVA = multivariate analysis of variance.

[4] Bonferroni-adjusted significance level: $p = 0.05/6 = 0.008$

[5] Bonferroni-adjusted significance level: $p = 0.05/10 = 0.005$

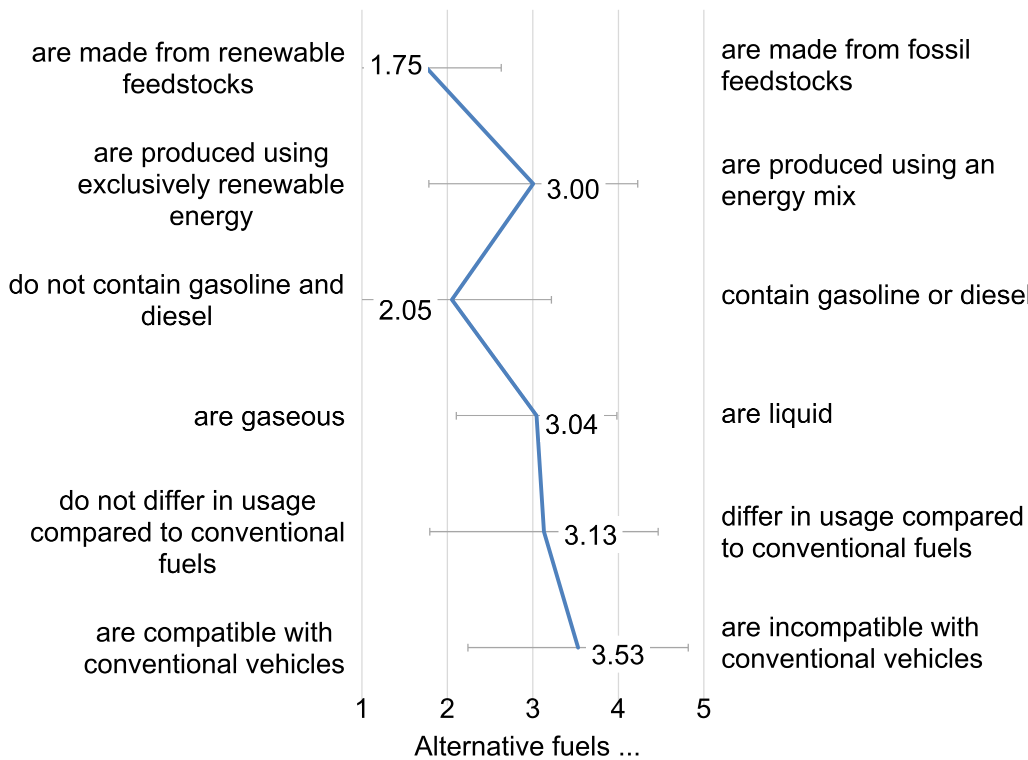

Fig. 2 Lay beliefs about alternative fuels (*n* = 208). Error bars indicate standard deviations

Table 2 t-test for deviations from scale midpoint (3) for the belief items (*n* = 208, *df* = 207)

Belief	*t*	*p*	Cohen's d
Renewable–fossil feedstocks	− 20.52	< 0.001	− 1.42
Renewable energy–energy mix		n.s.	
No diesel/gasoline–contains diesel gasoline	− 11.74	< 0.001	− 0.81
Gaseous–liquid		n.s.	
No difference–difference in usage		n.s.	
Compatible–incompatible	5.92	< 0.001	0.41

Table 3 t-test for deviations from scale midpoint (3) for the comparison of alternative fuels to diesel and gasoline (*n* = 208, *df* = 207)

Evaluative dimension	*t*	*p*	Cohen's d
Cleaner–dirtier combustion	− 25.67	< 0.001	− 1.78
More–less sustainable	− 28.88	< 0.001	− 2.00
Lower–higher CO_2 footprint	− 25.33	< 0.001	− 1.76
Less–more pollutant emissions	− 23.69	< 0.001	− 1.64
Smaller–higher land use		n.s.	
Safer–more dangerous	− 7.15	< 0.001	− 0.50
Less–more toxic	− 15.99	< 0.001	− 1.11
Cheaper–more expensive	6.22	< 0.001	0.43
Easier–more elaborate to use		n.s.	
Increased–decreased range	8.71	< 0.001	0.60

Perceptions of e-fuels vs. biofuels

To compare perceptions of different fuel types, biofuels and e-fuels were assessed on the same evaluative dimensions reflecting environmental effects, benefits, costs, and risks. The results for perceptions of biofuels and e-fuels are displayed in Fig. 4.

Both biofuels and e-fuels were evaluated rather positively: They were perceived as useful, environmentally friendly, safe to use, and to have a low CO_2 footprint. One-way repeated-measures ANOVAs showed significant differences between fuel types for the evaluation of production costs (Pillai's V $= 0.08$, $F(1, 125) = 11.10$, $p = 0.001$, $\eta_p^2 = 0.08$), safety of fuel usage (Pillai's V $= 0.22, F(1, 125) = 34.42, p < 0.001, \eta_p^2 = 0.22$), and resource consumption (Pillai's V $= 0.17, F(1, 125) = 25.13, p < 0.001, \eta_p^2 = 0.17$). Whereas biofuels were expected to be cheaper in production and to be safer to use than e-fuels, they were also believed to be in higher competition for resources with other sectors than e-fuels.

When asked about which of the two fuel types they would prefer given the same fuel price, 45.2% chose the e-fuel and 23.8% the biofuel (see Fig. 5). This shows that e-fuels were more preferred than biofuels. 30.2% of the sample had an equal preference for both fuel types and 0.8% wanted to use none of the fuels.

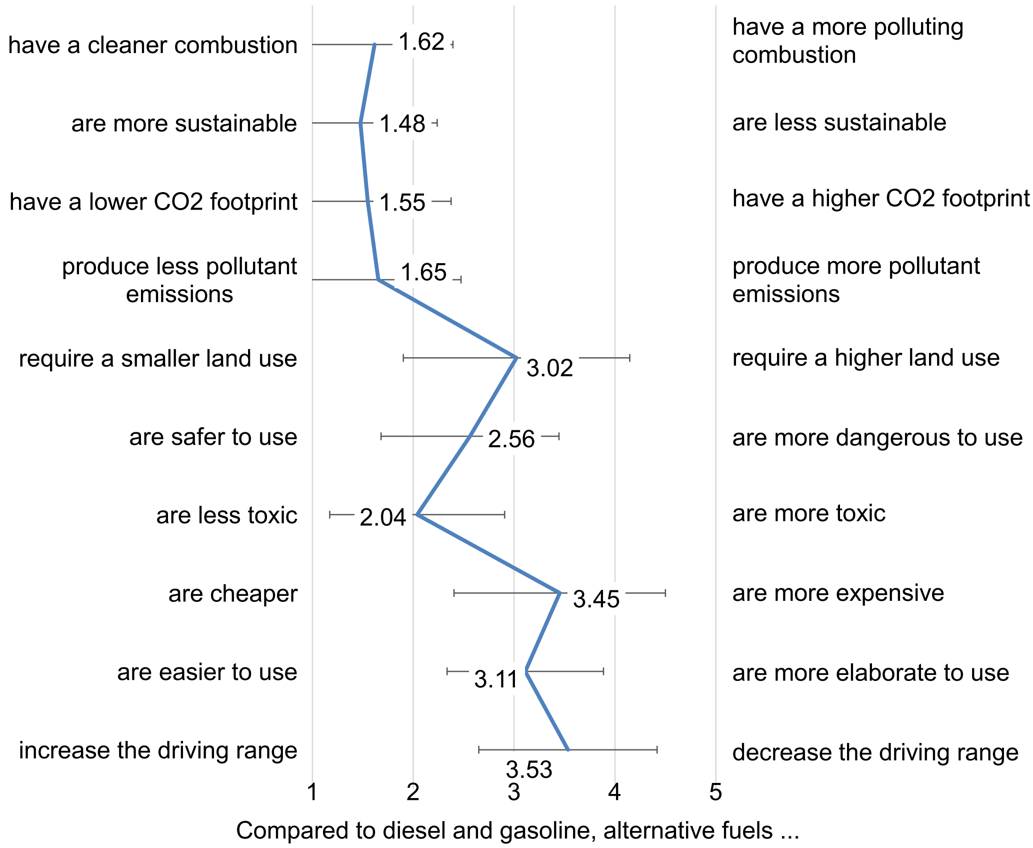

Fig. 3 Perceptions of alternative fuels compared to diesel and gasoline (n = 208). Error bars indicate standard deviations

In order to identify which groups of people preferred biofuels and e-fuels, an ANOVA was conducted with the fuel type preferences as groups[6] using the demographic and personality characteristics as dependent variables.[7]

Significant differences between the groups were found for gender, education, driving frequency, annual mileage, and self-assessed knowledge about alternative fuels (see Table 6 in the Appendix). Whereas in the group with biofuel preference there was a higher share of females, the group preferring e-fuels had a higher share of males. In the group with biofuel preference, the majority had a formal education of type 2 (high school degree or completed vocational training) while in the other two groups the majority had a formal education of type 3 (university degree or Ph.D.). The driving frequency and annual mileage also differed between the groups (see Table 6 in the Appendix). For self-assessed knowledge, the group preferring e-fuels felt slightly more informed about alternative fuels than the group preferring biofuels.

To investigate whether people with different fuel preferences also differed in their evaluation of biofuels and e-fuels, a MANOVA was conducted on the fuel preference groups. Table 4 contains the results. People who preferred biofuels rated biofuels as significantly more useful than respondents who preferred e-fuels. At the same time, the group with biofuel preference evaluated biofuels as significantly more environmentally friendly than the other two groups. A similar result was found for e-fuels: People who preferred e-fuels assessed e-fuels as significantly more environmentally friendly than the group with a biofuel preference. Apparently, preferences for a fuel type were attributed to differences in perceived benefits rather than to differences in costs and risks.

[6] The group “I would use none of the fuels” was left out because of its small size (0.8%).

[7] Considered were age, gender, education, place of residence, field expertise, technical self-efficacy, personal innovativeness, awareness and perceived responsibility for environment and climate change, vehicle propulsion type, dependency on car, driving frequency, annual mileage, self-assessed knowledge about alternative fuels, and interest in alternative fuels.

Table 4 MANOVA results for differences in the perception of biofuels and e-fuels for the fuel preference groups ($n = 125$)

Fuel type	Evaluative dimension	Group 1: equal preference ($n = 38$)	Group 2: biofuel preference ($n = 30$)	Group 3: e-fuel preference ($n = 57$)	Significance testing
Biofuels	Usefulness	$M = 4.11$ (SD = 0.83)	$M = 4.37$ (SD = 0.96)	$M = 3.67$ (SD = 1.01)	$F(2, 122) = 5.95, p = 0.003, \eta_p^2 = 0.09$ Post hoc test (Tukey): significant difference between groups 2 and 3 ($p = 0.004$)
	Eco-friendliness	$M = 4.03$ (SD = 0.79)	$M = 4.33$ (SD = 0.71)	$M = 3.53$ (SD = 0.97)	$F(2, 122) = 9.57, p < 0.001, \eta_p^2 = 0.14$ Post hoc test (Games–Howell): group 3 differs significantly from group 1 ($p = 0.019$) and group 2 ($p < 0.001$)
	Cheap production	$M = 2.82$ (SD = 0.95)	$M = 3.07$ (SD = 1.17)	$M = 2.74$ (SD = 0.92)	$p =$ *n.s.*
	Safe use	$M = 3.87$ (SD = 0.84)	$M = 4.17$ (SD = 0.87)	$M = 4.05$ (SD = 0.83)	$p =$ *n.s.*
	Low CO_2 footprint	$M = 3.55$ (SD = 1.03)	$M = 3.90$ (SD = 0.80)	$M = 3.53$ (SD = 0.91)	$p =$ *n.s.*
	Low competition for resources	$M = 2.66$ (SD = 1.17)	$M = 2.67$ (SD = 1.27)	$M = 2.74$ (SD = 1.26)	$p =$ *n.s.*
E-fuels	Usefulness	$M = 3.97$ (SD = 0.85)	$M = 3.70$ (SD = 1.15)	$M = 4.16$ (SD = 0.88)	$p =$ *n.s.*
	Eco-friendliness	$M = 3.87$ (SD = 0.78)	$M = 3.40$ (SD = 1.07)	$M = 4.02$ (SD = 0.69)	$F(2, 122) = 5.62, p = 0.005, \eta_p^2 = 0.08$ Post hoc test (Games–Howell): significant difference between groups 2 and 3 ($p = 0.018$)
	Cheap production	$M = 2.47$ (SD = 0.83)	$M = 2.37$ (SD = 1.16)	$M = 2.56$ (SD = 1.09)	$p =$ *n.s.*
	Safe use	$M = 3.58$ (SD = 0.76)	$M = 3.23$ (SD = 0.97)	$M = 3.56$ (SD = 0.98)	$p =$ *n.s.*
	Low CO_2 footprint	$M = 3.50$ (SD = 1.08)	$M = 3.53$ (SD = 1.04)	$M = 3.82$ (SD = 0.95)	$p =$ *n.s.*
	Low competition for resources	$M = 3.37$ (SD = 1.00) $M = 3.00$ (SD = 1.05)	$M = 3.60$ (SD = 1.19)	$p =$ *n.s.*	

Discussion

Insights into laypeople's beliefs about alternative fuels

The beliefs laypeople hold towards alternative fuels indicate that drivers expect considerable drawbacks from using alternative fuels, e.g., an incompatibility with conventional vehicles, a higher fuel cost, and a lower driving range compared to diesel and gasoline. Especially costs and a required retrofit or purchase of a new vehicle due to incompatibility with conventional vehicles could be serious barriers because these have been identified as vital decision criteria for alternative fuel preferences in previous research [27].

The perception of less toxic effects and higher safety of alternative fuels compared to conventional fuels confirm findings of Engelmann et al. [35] and extend their validity to CO_2-based fuels. However, that study revealed that on an absolute basis, perceived toxic effects and perceived safety were moderate for CO_2-based fuels, which indicates that they were not seen as completely safe.

Between two worlds: comparing lay beliefs to the fuel expert perspective

The general beliefs of the participating laypeople about alternative fuels (Fig. 2) are largely in line with technical reality, at least for certain types of alternative fuels: The fuels were believed to be made from renewable feedstock, which applies to both biofuels and e-fuels, but not to alternative fossil fuels such as LPG or CNG. In contrast, the energy input is believed to be exclusively renewable by some and an energy mix by others. Both can be the case, e.g., when producing e-fuels exclusively from renewable electricity vs. grid electricity, or when producing biomass with energy for farming and fuel production also derived from renewable vs. conventional sources. The finding that alternative fuels were perceived to not contain gasoline and diesel suggests that laypeople either expect a neat fuel rather than a blend component, or that they associate the term only with the blend component itself and not the mixture with gasoline or diesel. The beliefs about the state of matter, usage requirements, and vehicle compatibility, all of which were rather widely spread, also reflect technical reality in the sense that different alternative fuels have very different properties in these categories. However, it is unclear whether laypeople are aware of these differences or simply unsure about what to expect.

Similarly, the perceived differences between alternative fuels and gasoline and diesel (Fig. 3) are also in line with the actual technical performance of many alternative fuels. Alternative fuels were perceived to have less environmental harm regarding pollutant emissions as well as CO_2 footprint and general sustainability. These points are in line with the main development goals for (renewable) alternative fuels, and they are also fulfilled by many existing and proposed alternative fuel candidates. The perceived decrease in driving range is also in line with the lower energy density of most alternative fuels, while the perception of alternative fuels being more expensive is in line with the cost predictions for many (though not all) biofuels and e-fuels. The perception that alternative fuels are less toxic is partly in line with technical reality, as this holds for some alternative fuels, but not for all (e.g., methanol). The large spread in the perceived land use of alternative fuels may be related to the spread in land use between biofuels and e-fuels, with the former likely requiring more land. However, both biofuels and e-fuels likely require significantly more land than fossil fuels.

Recommendations for fuel design

Based on the findings, the following recommendations for a socially accepted fuel design are obtained:

Little to no barriers are vital for making the switch to alternative fuels because laypeople expect drawbacks in fuel usage compared to diesel and gasoline such as higher costs and a lower range. The role of costs may also depend on the general development of fossil fuel prices. Increasing fossil fuel prices makes it easier for alternative fuels based on biomass or renewable electricity to become economically competitive. Additionally, subsidies for alternative fuels or CO_2 taxation could also offset the higher costs of alternative fuels. To address concerns about fuel price and range, drivers should be transparently informed about costs and efforts required for switching to alternative fuels and about the political measures taken to facilitate alternative fuel adoption.

Environmental effects and low risks should be emphasized. They were perceived as advantages of alternative compared to conventional fuels and thus could be important enablers of alternative fuel adoption. This may not be limited to alternative fuel use in cars, but could also be important for their application in heavy-duty transport, shipping, and aviation because these effects concern the whole fuel lifecycle.

From an acceptance research perspective, the finding that laypeople expect alternative fuels to be made from *renewable resources* reveals biofuels and e-fuels to be more promising fuel candidates compared to alternative fossil fuels (such as LPG or CNG), which do not fulfill this renewable feedstock requirement. Moreover, because laypeople assume alternative fuels to not contain gasoline and diesel, fuel blends of alternative fuels with gasoline and diesel could be an inhibitor for acceptance if laypeople expect alternative fuels to be fully made from renewable feedstocks. However, it remains unclear if a blend with a renewable component is nevertheless perceived as an 'improvement' to conventional fuels and preferred by drivers at the fuel station. If a blend with gasoline or diesel has advantages to drivers compared to a neat renewable fuel (e.g., no required car retrofitting and a higher driving range), it is possible that drivers' preferences for the blend or neat fuel can vary. Therefore, future research should compare perceptions of alternative fuel blends vs. neat fuels to uncover decision criteria and preferences for the different fuel options and to reveal whether laypeople distinguish between blends and neat fuels. This is especially important since a lower range was perceived as drawback of alternative fuels compared to conventional fuels.

Summing up, the following guidelines should be respected for alternative fuels in general:

- Ensure environmentally friendly production and use (e.g., low CO_2 footprint and less pollutant emissions).
- Aim for cost-effective fuel production to reduce fuel prices.
- Ensure a sufficient driving range.
- Minimize toxic effects.
- Alternative fuels should not contain conventional diesel or gasoline (if blends with diesel or gasoline are used, these should be transparently labeled as such).
- Alternative fuels are perceived as different from existing fuels—therefore, specific information and communication efforts should be undertaken to inform laypeople adequately which impacts alternative fuels have.

Insights into preferences and perceptions of biofuels vs. e-fuels

The direct comparison of the acceptance of e-fuels and biofuels has revealed similarities and differences between both fuel types. Positive benefit perceptions and unspecific risk perceptions were found for both "alternative" fuels and validate past research [35, 37, 53]. For both fuels, the perceived environmental benefits are prominent, which is in line with results from previous studies examining biofuel and e-fuel acceptance separately [32, 37, 53, 54].

However, the revealed differences in perceptions between e-fuels and biofuels highlight possible acceptance barriers for both fuel types. As a possible inhibitor for biofuel adoption, the perceived competition for resources was identified. The perceived higher competition for resources in the biofuel context compared to the e-fuel context could possibly be explained by a belief that the feedstock use (if food crops are used for biofuel production) or the land use for producing biofuel feedstocks (if biomass is used for biofuel production) could be in competition with food supply. A competition between biomass use for fuels and food as well as increasing food prices due to biofuel production have been revealed to be obstacles for biofuel acceptance in previous research [34, 40, 42, 43]. To address concerns about resource competition, transparent information on the feedstock basis and resource consumption should be given to laypeople: Are biofuels produced solely from waste or inedible crops (e.g., straw, wood waste) or are crops or land used that could be used for other important purposes (e.g., food production)?

In contrast, possible acceptance barriers for e-fuels could be the perception of higher costs and higher risks compared to biofuels. Since the price for alternative fuels was found to be decisive for drivers [27], concerns about high fuel costs are even more important. However, previous research revealed some contradictory findings when it comes to the expected e-fuel price: In a recent study [53] CO_2-based fuels were not perceived as particularly expensive. In line with this, Arning et al. [54] reported that laypeople evaluated CO_2-based fuels as neither cheap nor expensive. A possible reason for the different evaluation could be that in our study the focus on both biofuels and e-fuels influenced evaluations of e-fuels so that they were rated as relatively expensive compared to biofuels. Another explanation for the diverging results could be the age of study respondents: In our study respondents were on average younger and more often students than the respondents in the other studies [53, 54]. The younger age or student status could be related to a possibly lower financial status and thus may have led to a different evaluation of the terms "cheap" and "expensive" than in a more balanced sample.

Regarding the second barrier, i.e., perceived risks, it was found that although risks from e-fuels were rated higher than risks from biofuels, perceived e-fuel risks were still rather low. Thus, it is not expected that e-fuels are instantly rejected due to fears of specific risks. Still, it would be insightful to understand how the higher risk perception of e-fuels is composed and which target is perceived to be most affected by risks (e.g., the environment, the health of drivers, employees at the fuel production plant or residents living nearby). Therefore, future research should investigate perceived risks of e-fuels and biofuels in more detail to trace down the facets that constitute the risk perception. For example, it is known from biofuels research that health effects have a higher weight than environmental concerns when it comes to the willingness to pay for biofuels [46].

The analysis of preferences for e-fuels and biofuels however has shown that e-fuels were preferred over biofuels and that the biofuel preference group and the e-fuel preference group mainly differed in the benefit perceptions of the two fuel types. This is in line with previous research on biofuels and e-fuels which found a positive impact of benefit perceptions on fuel attitudes [37, 53].

Moreover, different user profiles had been identified: People with a preference for e-fuels were more often male, had a higher formal education, and drove less frequently on a regular basis than people with a preference for biofuels (although they had a lower share of non-drivers and were more often high-mileage drivers). These findings largely added to comprehending user diversity for e-fuels, which is not well understood, and corroborated past research on biofuels. The higher share of females among the group with biofuel preference compared to the groups with e-fuel preference and with equal preferences for both fuel types corroborates previous findings that women have a more positive perception of biofuels [33, 49]. Also, the higher share of people with a high school degree or completed vocational training in the biofuel group compared to the higher share of people with university degree in the e-fuel and equal preference groups validates past research which found a higher formal education linked to more negative perceptions of biofuel use [50].

Results on self-assessed knowledge leave an incomplete picture as the omnibus effect in the MANOVA between the three preference groups could not be attributed to a significant specific group difference. On a descriptive level, e-fuel-preferring people felt on average more informed than biofuel-preferring people. Previous research (e.g., [49, 51]), has identified knowledge (both objective and self-assessed) as relevant factor affecting biofuel perceptions but the directions of the effect (positive or negative) were mixed. While some studies found biofuels perceptions and acceptance to be more positive with a higher objective or self-assessed knowledge [33, 51], others revealed a negative effect [49, 52]. Thus, future research should investigate the impact of previous knowledge on perceptions of different fuel types more closely.

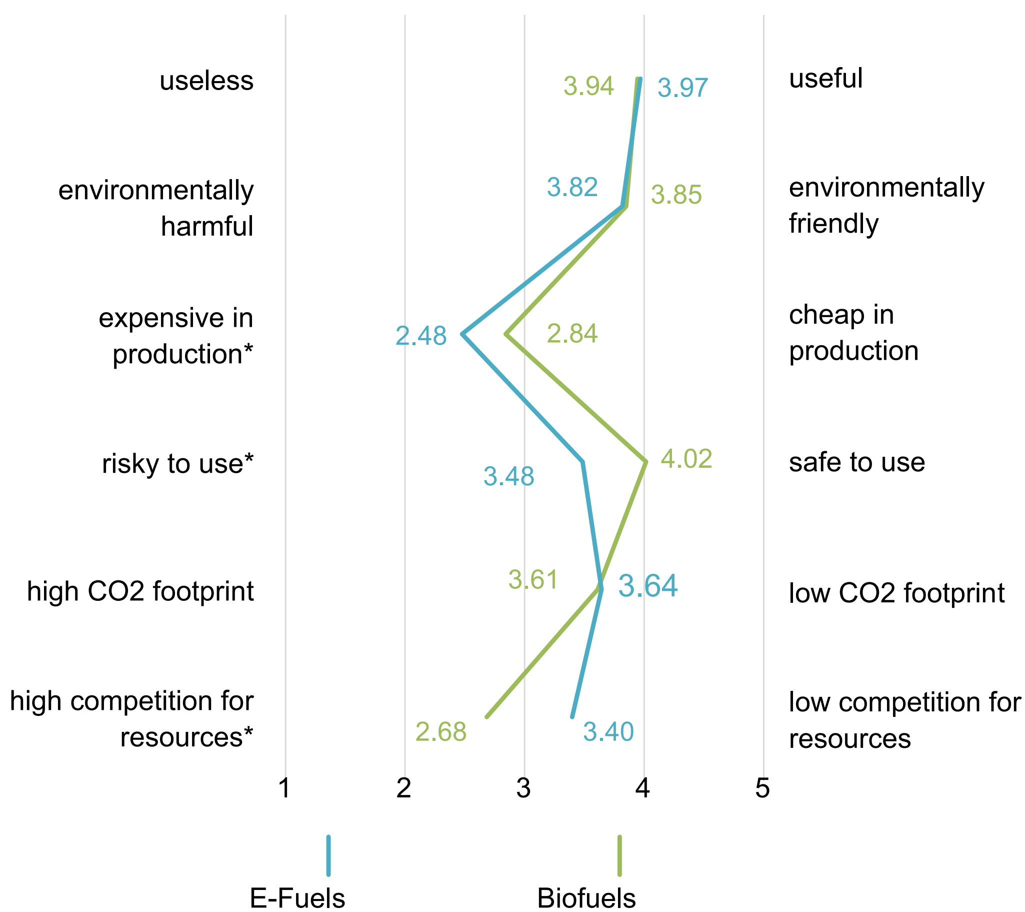

Fig. 4 Perceptions of biofuels and e-fuels ($n = 126$). Significant differences (Bonferroni-adjusted significant level: $p \leq 0.008$) are marked by asterisks

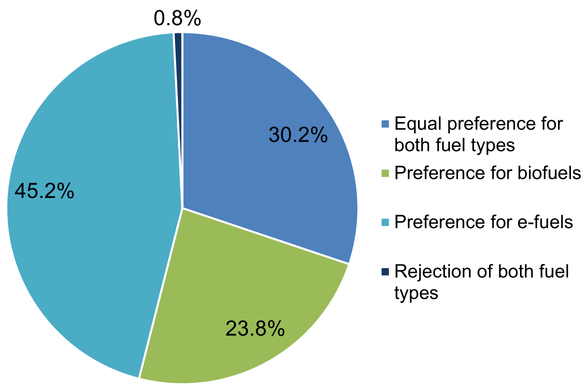

Fig. 5 Preferences for using biofuels and e-fuels ($n = 126$)

Lay and expert view on fuel types: congruence and possible misconceptions

In the comparison between the perceptions of biofuels and e-fuels (Fig. 4), most points can also be matched with aspects of the actual technical performance, such as e-fuels being more expensive than biofuels [25]. The perceived higher competition for resources of biofuels is in line with the differences in water use and land requirement. If they refer to competition with food production, this only applies to first-generation biofuels, which may still be prevalent in the perception of laypeople.

The results of the present study also match insights from technical expert perspective that for e-fuels higher production costs are to be expected compared to conventional fuels and to biofuels [24].

The aspect of safety for which significant perceived differences between biofuels and e-fuels were found is harder to assess from a technical point of view.

One aspect that may explain the perceived difference is that some (but not all) common e-fuels are stored as gases in high-pressure tanks (e.g., hydrogen, methane, or dimethyl ether), while biofuels are more commonly liquid. Such high-pressure tanks may be perceived as an additional safety hazard for e-fuels. To this end, future research should further investigate to what extent the state of matter of a fuel affects the perception of safety, and whether laypeople in fact imagine biofuels to be liquid and e-fuels to be gaseous. The latter could explain why the participants were undecided on whether alternative fuels in general are liquid or gaseous.

Another explanation for the higher risk perception of e-fuels compared to biofuels could be that biofuels, which have been on the market for a longer period already (e.g., ethanol-blend fuel E10), are perceived as more established and thus as more familiar and in turn, elicit less concerns by laypeople. However, the experience with E10 in Germany, where drivers were reluctant in adopting E10 [12], has shown that biofuels can also lead to worries. This indicates that risk perceptions of fuel types are quite complex, and that future research requires a focus on underlying assumptions and influencing factors of risk perceptions and their interrelation.

The comparatively lower risk perception of biofuels could also be explained by a more positive connotation of the term "bio". This could have evoked associations of organic or environmentally friendly production or naturalness [63], or even more generally life and nature, whereas e-fuels might evoke associations with electricity (the power system) that are more likely associated with risks. The positive meaning of "bio" in the fuel context is supported by findings of Cacciatore et al. [64] that the term "biofuel" is more positively evaluated than the term "ethanol". Still, these explanations remain speculative without empirical evidence, thus the underlying beliefs and reasons for the higher risk perception of e-fuels need further research.

Recommendations for the selection of fuel types and production routes

The above findings on the preferences of potential fuel users between biofuels and e-fuels have a key implication for the development of alternative fuels and lead to the following recommendations for research and decision-making:

Both fuel types may have a significant share of fuels users preferring one or the other, potentially with distinct user profiles. This suggests that neither biofuels nor e-fuels should be discarded based on acceptance criteria, and that it is instead reasonable to keep developing both fuel types and consider the identified consumer segments as target groups in fuel design.

Since benefit perceptions have been revealed as crucial for fuel preferences, both fuel types however need clear advantages and these need to be transparently and comprehensibly communicated.

In particular, low environmental impacts were given as main reasons to prefer either biofuels or e-fuels over the other. This underlines the importance of careful analysis of true environmental impacts via life cycle assessments as well as transparent communication of these effects. Similarly, it confirms the notion that low environmental impacts should be a key performance metric for fuel development.

The perceived higher fuel costs of e-fuels compared to biofuels indicate that cost optimization of production processes for e-fuels should be targeted. Another possibility to achieve lower e-fuel costs could be subsidies. People with a preference for e-fuels differed mainly in the perception of higher benefits from people with preference for biofuels. Therefore, showing the cost-benefit relation of e-fuels (higher costs but also possibly favorable environmental effects, [24]) is essential.

Finally, the observed differences in the groups of users preferring either biofuels or e-fuels could ultimately inform the design of different fuels targeted at these two (or potentially even more) distinct user groups. To this end, a more detailed evaluation is required to identify which performance criteria are the most relevant to which group. This type of information may even be embedded directly in optimization-based methods for the design of fuels, their production processes, or both if they come in the form of constraints (e.g., minimum driving range, lower greenhouse gas emissions than some target), as quantitative weights of different performance criteria, or even as a mathematical model that predicts acceptance or adoption likeliness for that group as a function of technical properties of the fuel or production pathway.

Summing up, the selection of fuel candidates should be aimed at optimizing the following criteria:

- For biofuels:
  - Use primarily waste biomass as feedstock such as wood residues (to avoid a perceived competition for resources and a high land use).
- For e-fuels:
  - Ensure and transparently communicate fuel safety.
  - Make e-fuels financially competitive to biofuels.

Limitations and future research

The current study has provided a valuable understanding of the beliefs and expectations of laypeople towards alternative fuels. At the same time, the findings raise some methodological issues and have uncovered important future research duties.

For some of the evaluative dimensions for alternative fuels an "indecisiveness" was found, e.g., whether alternative fuels are gaseous or liquid or whether renewable energy is used in the production or not. The reasons for this indecisiveness should be investigated in future research: Does this reflect true indecisiveness (as "don't know"), indifference (as "does not matter to me"), or rather an awareness that the term "alternative fuel" refers to a broad variety of different fuels that can differ in their properties and production routes?

Also, the effects of user diversity on the beliefs of alternative fuels should be explored to uncover whether perceptions of the term "alternative fuels" differ with sociodemographic variables, attitudes, and mobility behavior. For this purpose, it would be insightful to validate the findings with a larger sample representative for Germany with respect to demographics to capture the view of an entire population.

Another open question is whether the laypeople represented e-fuels and biofuels solely as an end-product or if they also considered the fuel production routes in their evaluations. The latter is supported by results from Simons et al. [53], in which the perceptions of CO_2-based fuels as a product were influenced by perceptions of the underlying production technology. Future research should investigate which dimension (production process or end-product) influences perceptions the most and whether preferences and evaluations of biofuels and e-fuels change when expert information about environmental effects, risks, and costs of fuel production and fuel usage is given. Offermann-van Heek et al. [36] has shown that providing laypeople with technically accurate information on environmental effects can significantly change preferences for CO_2-based fuel production towards more environmentally favorable production options.

A final research concern refers to the narrow one-country scope on car use in Germany. Since current EU-law and political plans in Germany aim at supporting electromobility and abolishing combustion engines for cars from 2035 on, future research needs to tackle the perspective on different transport sectors with a higher future potential for alternative fuel use (e.g., heavy-duty transport, shipping, and aviation). Future studies should expand the scope to include different countries and cultures because in countries with no plans to abolish combustion engines, alternative fuels may play a more important role in individual transport compared to Germany.

Conclusion

The defossilization of mobility is a key goal in combating climate change, which is not only extremely challenging from a technical point of view (e.g., development of fuel alternatives, of production routes, and combustion technology), but also has to take socio-political factors into account during implementation and adoption. The empirical analysis of social perceptions of alternative fuels in this study provided valuable information on what expectations laypersons associate with alternative fuels. The perceptions are consistent with the current technical challenges in the development of alternative fuels in terms of price, energy supply during production, and technical performance, and can certainly be understood as demands on technical development from the users' perspective. Even if e-fuels and biofuels carry the same label of "alternative fuels", they are perceived differently, in terms of core characteristics like safety, ethical aspects like resource competitiveness, and economic aspects, and associated with different evaluative assessments, which can seriously modulate acceptance (in both directions). In order to achieve a successful transformation towards lower-carbon mobility, it is extremely important to know these perceptions and requirements of potential adopters of alternative fuels, to take them into account in technical development, production and implementation, and to adequately address them in communication strategies.

Appendix

Constructs and item statistics

Table 5 Constructs and item statistics ($n = 208$)

Construct	Source	Item no.	Items	Cronbach's alpha
Awareness for environment and climate change	[55–57]	6	I feel worried about the environmental conditions under which our children and grandchildren probably have to live. If we carry on like before, we are heading towards an environmental catastrophe. In my estimation the environmental problem is greatly exaggerated by media and politicians. (recoded) For the sake of the environment, we should all be prepared to limit our current standard of living. I personally feel that it is important to think about the environment in my everyday driving behavior. I am prepared to change my mobility behavior in order to protect the environment.	0.85
Perceived responsibility for environmental problems	[58]	2	My car use contributes to environmental problems. The currently occurring environmental problems are mainly caused by others. (recoded)	0.46
Technical self-efficacy	[59]	4	I can solve quite a few of the technical problems I am confronted with on my own. I really enjoy solving technical problems. Because I got along well with previous technical problems, I optimistically look forward to future technical problems. I feel so helpless when interacting with technical devices that I rather keep my hands off them.	0.90
Personal innovativeness ($n = 207$)	[60]	4	I regularly look out for new products. I often search for information about new technologies and products that could be of interest to me. Most often, I am the first of my friends to test new products. I find it interesting to test new products.	0.88
Attitude towards driving ($n = 207$)	[61]	7	For me, the car has instrumental functions only. (recoded) I only have a car to travel from A to B. (recoded) I love driving. A car provides status and prestige. I feel free and independent if I drive. I like to drive just for the fun. My car shows who and what I am.	0.82
Self-assessed knowledge about alternative fuels	[35]	2	I feel well informed about alternative fuels. I feel well informed about the production of alternative fuels.	0.90
Acceptance of alternative fuels	[35]	4	I do not want to use alternative fuels for driving a car. (recoded) I think the use of alternative fuels in road transport is a bad idea. (recoded) I am willing to refuel with alternative fuels. I would prefer alternative fuels to conventional fuels for driving.	0.75

Group comparisons

Table 6 Group comparisons (ANOVAs and Chi-square tests) for differences in socio-demographics and personality characteristics ($n = 125$)

Socio-demographics and personality	Group 1: equal preference ($n = 38$)	Group 2: biofuel preference ($n = 30$)	Group 3: e-fuel preference ($n = 57$)	Significance testing
Age	$M = 31.4$ years (SD = 10.7)	$M = 35.8$ years (SD = 13.4)	$M = 36.5$ years (SD = 16.0)	$p =$ n.s.
Gender	50.0% female, 50.0% male	63.3% female, 36.7% male	29.8% female, 70.2% male	$\chi^2(2) = 9.75, p = 0.008$
Education*	2.6% Education Level 1, 26.3% Education Level 2, 71.1% Education Level 3	6.7% Education Level 1, 60.0% Education Level 2, 33.3% Education Level 3	3.5% Education Level 1, 29.8% Education Level 2, 66.7% Education Level 3	$\chi^2(4) = 11.89, p = 0.018$
Place of residence	55.3% city center, 36.8% city outskirts / suburb, 7.9% rural area	53.3% city center, 23.3% city outskirts / suburb, 23.3% rural area	42.1% city center, 40.4% city outskirts / suburb, 17.5% rural area	$p =$ n.s.
Field Expertise	13.2% yes, 86.8% no	10.0% yes, 90.0% no	22.8% yes, 77.2% no	$p =$ n.s.
Technical self-efficacy	$M = 4.36$ (SD = 1.16)	$M = 3.88$ (SD = 1.30)	$M = 4.35$ (SD = 1.19)	$p =$ n.s.
Personal innovativeness	$M = 3.52$ (SD = 1.02)	$M = 3.33$ (SD = 1.06)	$M = 3.56$ (SD = 1.29)	$p =$ n.s.
Awareness for environment and climate change	$M = 4.77$ (SD = 0.91)	$M = 4.86$ (SD = 0.72)	$M = 4.78$ (SD = 0.71)	$p =$ n.s.
Perceived responsibility for environmental problems	$M = 4.11$ (SD = 0.91)	$M = 3.63$ (SD = 1.03)	$M = 4.01$ (SD = 0.96)	$p =$ n.s.
Vehicle propulsion type	64.9% gasoline, 24.3% diesel, 5.4% EV, 2.7% hybrid, 2.7% gas, 0% other	69.0% gasoline, 24.1% diesel, 0% EV, 3.4% hybrid, 0% gas, 3.4% other	67.9% gasoline, 25.0% diesel, 1.8% EV, 0% hybrid, 0% gas, 5.4% other	$p =$ n.s.
Car dependency	$M = 3.24$ (SD = 1.78)	$M = 3.70$ (SD = 1.95)	$M = 3.56$ (SD = 1.81)	$p =$ n.s.
Driving frequency (before COVID-19)	2.6% never, 57.9% on a yearly or monthly basis, 39.5% on a weekly or daily basis	20.0% never, 16.7% on a yearly or monthly basis, 63.3% on a weekly or daily basis	3.5% never, 40.4% on a yearly or monthly basis, 56.1% on a weekly or daily basis	$\chi^2(4) = 18.16, p = 0.001$
Annual mileage	7.9% prefer not to say / don't know, 65.8% up to 10,000 km, 18.4% > 10,000–20,000 km, 7.9% > 20,000 km	23.3% prefer not to say / don't know, 43.3% up to 10,000 km, 20.0% > 10,000–20,000 km, 13.3% > 20,000 km	5.3% prefer not to say / don't know, 43.9% up to 10,000 km, 31.6% > 10,000–20,000 km, 19.3% > 20,000 km	$\chi^2(6) = 13.12, p = 0.041$
Self-assessed knowledge about alternative fuels	$M = 2.63$ (SD = 1.36)	$M = 2.62$ (SD = 1.10)	$M = 3.23$ (SD = 1.18)	$F(2,122) = 3.79, p = 0.025, \eta_p^2 = 0.06$, Post hoc test (Tukey): difference between groups 2 and 3 almost reaches significance level: ($p = 0.055$)
Interest in alternative fuels	$M = 4.29$ (SD = 1.18)	$M = 4.30$ (SD = 1.02)	$M = 4.75$ (SD = 1.02)	$p =$ n.s.

*Education Level 1: primary, secondary, or middle school; Education Level 2: high school degree or completed vocational training; Education Level 3: university degree or Ph.D

Acknowledgements
The authors would like to thank Julia Arndt for research support. Many thanks go to the fruitful discussions at the Fuel Science Conference 2022 of the Cluster of Excellence "The Fuel Science Center".

Author contributions
Conceptualization: [AL, DB, KA, MZ]; methodology: [AL, MZ]; formal analysis and investigation: [AL]; writing—original draft preparation: [AL, DB, KA, MZ]; writing—review and editing: [AL, DB, KA, MZ]; funding acquisition: [MZ]; resources: [MZ]; supervision: [MZ].

Funding
Open Access funding enabled and organized by Projekt DEAL. This 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.

Availability of data and materials
The datasets used and analyzed during the current study are available from the corresponding author on reasonable request for research issues.

Declarations

Ethics approval and consent to participate
We did not seek ethical approval from the ethics committee, as our study falls in the category where no such approval is necessary in Germany. This category spans all non-invasive, non-clinical research on human subjects, where subjects are transparently informed about the purpose, aim, and risks of the studies and when these risks are reasonably low. Prior to starting the procedure, they were informed that it is of high importance to understand free opinions and attitudes on sustainable mobility from the citizens' perspective and that we were very happy if they would share their opinions with us. Still, however we stressed that they are free in taking part or not and their participation was completely voluntary. The participants were not reimbursed for taking part in the study. Further, we ensured a high standard privacy protection and let the participants know that none of their answers can be referred to them as persons. After these careful explanations participants reported to feel well informed about the purpose and the aim of the study and their freedom to quit participation at any time. All participants consented to take part in the study and were of legal age. Regarding the privacy policy explanations, the participants reported to understand that high standards were applied and deliberately accepted participation. Participant privacy is a key value that our university has committed itself to uphold. From the comments in the open question fields at the end of the survey, we learnt that those participants were interested in the topic and were keen to look at the results, which we assured them to receive.

Consent for publication
Participants provide data and this raw data is anonymized as data are by default stored in anonymized or aggregated form without the possibility of inferring details of individual persons. Nonetheless, this raw but anonymized/aggregated data can be made available on request for the sake of further research by the authors or the Chair of Communication Science at RWTH Aachen University. The participants were informed that the results of the study were intended to be used for scientific purposes and solely to be analyzed by the Chair of Communication Science at RWTH Aachen University. Also, they were informed that due to the applied high standard privacy protection none of their answers can be referred to them as persons. After these careful explanations on the use of their data, participants reported to feel well informed about the purpose and the aim of the study and their freedom to quit participation at any time as well as that high standards for privacy protection were applied. All participants were of legal age and consented to take part in the study under these circumstances. Our manuscript does not contain any individual details, videos, or images of individual persons.

Competing interests
The authors declare that they have no competing interests.

Author details
[1]Human-Computer Interaction Center (HCIC)/Chair of Communication Science, RWTH Aachen University, Campus-Boulevard 57, 52074 Aachen, Germany. [2]Process Systems Engineering (AVT.SVT), RWTH Aachen University, Forckenbeckstraße 51, 52074 Aachen, Germany. [3]Department of Chemical Engineering, KU Leuven, Celestijnenlaan 200F, 3001 Leuven, Belgium. [4]Junior Professor for Risk Perception and Communication, Institute for Linguistics and Communication Science, RWTH Aachen University, Campus-Boulevard 57, 52074 Aachen, Germany.

Received: 15 November 2022 Accepted: 31 August 2023
Published online: 26 September 2023

References

1. Follmer R, Gruschwitz D (2019) Mobility in Germany—Short Report. Transport Volume—Structure—Trends. Edition 4.0 of the study by infas, DLR, IVT and infas 360 on behalf of the Federal Ministry of Transport and Digital Infrastructure (BMVI). FE no. 70.904/15, (www.mobilitaet-in-deutschland.de)
2. Schubach E, Zimmermann J, Noack P, Neyer FJ (2016) Me, Myself, and Mobility: the relevance of region for young adults' identity development. Eur J Pers 30(2):189–200
3. Deutz S, Bongartz D, Heuser B, Kätelhön A, Schulze Langenhorst L, Omari A, Walters M, Klankermayer J, Leitner W, Mitsos A, Pischinger S, Bardow A (2018) Cleaner production of cleaner fuels: Wind-to-wheel–environmental assessment of CO_2-based oxymethylene ether as a drop-in fuel. Energy Environ Sci 11(2):331–343
4. Nemoto EH, Issaoui R, Korbee D, Jaroudi I, Fournier G (2021) How to measure the impacts of shared automated electric vehicles on urban mobility. Transp Res Part D: Transp Environ 93:102766
5. Huijts NMA, Molin EJE, Steg L (2012) Psychological factors influencing sustainable energy technology acceptance: a review-based comprehensive framework. Renew Sustain Energy Rev 16(1):525–531
6. Bearth A, Siegrist M (2016) Are risk or benefit perceptions more important for public acceptance of innovative food technologies: a meta-analysis. Trends Food Sci Technol 49:14–23
7. Murata A, Nakamura T, Karwowski W (2015) Influence of cognitive biases in distorting decision making and leading to critical unfavorable incidents. Safety 1(1):44–58
8. Lockton D (2012) Cognitive biases, heuristics and decision-making in design for behaviour change. (http://danlockton.co.uk)
9. Gigerenzer G (1997) Bounded rationality: models of fast and frugal inference. Swiss J Econ Stat 133(2/2):201–218
10. Bruhn T, Naims H, Olfe-Kräutlein B (2016) Separating the debate on CO_2 utilisation from carbon capture and storage. Environ Sci Policy 60:38–43
11. Zaunbrecher BS, Bexten T, Wirsum M, Ziefle M (2016) What is stored, why, and how? Mental models, knowledge, and public acceptance of hydrogen storage. Energy Procedia 99:108–119
12. Tosun J (2018) The behaviour of suppliers and consumers in mandated markets: the introduction of the ethanol–petrol blend E10 in Germany. J Environ Planning Policy Manage 20(1):1–15
13. Osman AI, Mehta N, Elgarahy AM, Al-Hinai A, Al-Muhtaseb AH, Rooney DW (2021) Conversion of biomass to biofuels and life cycle assessment: a review. Environ Chem Lett 19(6):4075–4118
14. Zinoviev S, Müller-Langer F, Das P, Bertero N, Fornasiero P, Kaltschmitt M, Centi G, Miertus S (2010) Next-generation biofuels: survey of emerging technologies and sustainability issues. Chemsuschem 3(10):1106–1133
15. König A, Siska M, Schweidtmann AM, Rittig JG, Viell J, Mitsos A, Dahmen M (2021) Designing production-optimal alternative fuels for conventional, flexible-fuel, and ultra-high efficiency engines. Chem Eng Sci 237:116562
16. Schiebahn S, Grube T, Robinius M, Zhao L, Otto A, Kumar B, Weber M, Stolten D (2013) Power to gas. In: Stolten D, Scherer V (eds) Transition to renewable energy systems. Wiley-VCH, Weinheim, pp 813–848
17. Goeppert A, Czaun M, Jones J-P, Prakash GKS, Olah GA (2014) Recycling of carbon dioxide to methanol and derived products—closing the loop. Chem Soc Rev 43:7995–8048

18. König DH, Baucks N, Dietrich RU, Wörner A (2015) Simulation and evaluation of a process concept for the generation of synthetic fuel from CO_2 and H_2. Energy 91:833–841
19. Müller LJ, Kätelhön A, Bringezu S, McCoy S, Suh S, Edwards R, Sick V, Kaiser S, Cuéllar-Franca R, El Khamlichi A, Lee JH, von der Assen N, Bardow A (2020) The carbon footprint of the carbon feedstock CO_2. Energy Environ Sci 13(9):2979–2992
20. Omari A, Heuser B, Pischinger S (2017) Potential of oxymethylenether-diesel blends for ultra-low emission engines. Fuel 209:232–237
21. Bongartz D, Doré L, Eichler K, Grube T, Heuser B, Hombach LE, Robinius M, Pischinger S, Stolten D, Walther G, Mitsos A (2018) Comparison of light-duty transportation fuels produced from renewable hydrogen and green carbon dioxide. Appl Energy 231:757–767
22. Pèlerin D, Gaukel K, Härtl M, Jacob E, Wachtmeister G (2020) Potentials to simplify the engine system using the alternative diesel fuels oxymethylene ether OME_1 and OME_{3-6} on a heavy-duty engine. Fuel 259:116231
23. Agarwal AK, Gupta T, Kothari A (2011) Particulate emissions from biodiesel vs diesel fuelled compression ignition engine. Renew Sustain Energy Rev 15(6):3278–3300
24. König A, Ulonska K, Mitsos A, Viell J (2019) Optimal applications and combinations of renewable fuel production from biomass and electricity. Energy Fuels 33(2):1659–1672
25. Brynolf S, Taljegard M, Grahn M, Hansson J (2018) Electrofuels for the transport sector: a review of production costs. Renew Sustain Energy Rev 81:1887–1905
26. Schmidt P, Batteiger V, Roth A, Weindorf W, Raksha T (2018) Power-to-liquids as renewable fuel option for aviation: a review. Chem Ing Tec 90(1–2):127–140
27. Linzenich A, Arning K, Bongartz D, Mitsos A, Ziefle M (2019) What fuels the adoption of alternative fuels? Examining preferences of German car drivers for fuel innovations. Appl Energy 249:222–236
28. Hackbarth A, Madlener R (2013) Consumer preferences for alternative fuel vehicles: a discrete choice analysis. Transp Res Part D: Transp Environ 25:5–17
29. Hoen A, Koetse MJ (2014) A choice experiment on alternative fuel vehicle preferences of private car owners in the Netherlands. Transp Res Part A Policy Pract 61:199–215
30. Kowalska-Pyzalska A, Kott M, Kott J (2021) How much Polish consumers know about alternative fuel vehicles? Impact of knowledge on the willingness to buy. Energies 14(5):1438
31. Hackbarth A, Madlener R (2016) Willingness-to-pay for alternative fuel vehicle characteristics: a stated choice study for Germany. Transp Res Part A Policy Pract 85:89–111
32. Chaiyapa W, Nguyen KN, Ahmed A, Vu QTH, Bueno M, Wang Z, Nguyen KT, Nguyen NT, Duong TT, Dinh UTT, Sjögren A, Le PTK, Nguyen TD, Nguyen HTA, Ikeda I, Esteban M (2021) Public perception of biofuel usage in Vietnam. Biofuels 12(1):21–33
33. Gracia A, Barreiro-Hurlé J, Pérez y Pérez L (2018) Overcoming the barriers for biodiesel use in Spain: an analysis of the role of convenience and price. J Cleaner Prod 172:391–401
34. Herbes C, Chouvellon S, Lacombe J (2018) Towards marketing biomethane in France—French consumers' perception of biomethane. Energy Sustain Soc 8(1):37
35. 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 8:579814
36. Offermann-van Heek J, Arning K, Sternberg A, Bardow A, Ziefle M (2020) Assessing public acceptance of the life cycle of CO_2-based fuels: Does information make the difference? Energy Policy 143:111586
37. Amin L, Hashim H, Mahadi Z, Ibrahim M, Ismail K (2017) Determinants of stakeholders' attitudes towards biodiesel. Biotechnol Biofuels 10(1):219
38. Savvanidou E, Zervas E, Tsagarakis KP (2010) Public acceptance of biofuels. Energy Policy 38(7):3482–3488
39. Mabumbo D, Mafongoya P (2019) Motorists' perceptions and attitudes towards ethanol blended fuel in Zimbabwe. J Energy Power Eng 13(2):68–79
40 Skipper D, Van de Velde L, Popp M, Vickery G, Van Huylenbroeck G, Verbeke W (2009) Consumers' perceptions regarding tradeoffs between food and fuel expenditures: a case study of U.S. and Belgian fuel users. Biomass Bioenergy 33(6–7):973–987
41. Dragojlovic N, Einsiedel E (2014) The polarization of public opinion on biofuels in North America: key drivers and future trends. Biofuels 5(3):233–247
42. Tan KT, Lee KT, Mohamed AR (2008) Role of energy policy in renewable energy accomplishment: the case of second-generation bioethanol. Energy Policy 36(9):3360–3365
43. Dragojlovic N, Einsiedel E (2015) What drives public acceptance of second-generation biofuels? Evidence from Canada. Biomass Bioenergy 75:201–212
44. Delshad AB, Raymond L, Sawicki V, Wegener DT (2010) Public attitudes toward political and technological options for biofuels. Energy Policy 38(7):3414–3425
45. Radics RI, Dasmohapatra S, Kelley SS (2016) Public perception of bioenergy in North Carolina and Tennessee. Energy Sustain Soc 6(1):17
46. Winden M, Cruze N, Haab T, Bakshi B (2014) Integrating life-cycle assessment and choice analysis for alternative fuel valuation. Ecol Econ 102:83–93
47. Van de Velde L, Verbeke W, Popp M, Buysse J, Van Huylenbroeck G (2009) Perceived importance of fuel characteristics and its match with consumer beliefs about biofuels in Belgium. Energy Policy 37(8):3183–3193
48. Zhang Y, Yu Y, Li T, Zou B (2011) Analyzing Chinese consumers' perception for biofuels implementation: the private vehicles owner's investigating in Nanjing. Renew Sustain Energy Rev 15(5):2299–2309
49. Cacciatore MA, Scheufele DA, Binder AR, Shaw BR (2010) Public attitudes toward biofuels: effects of knowledge, political partisanship, and media use. Energy Policy 38(7):3414–3425
50. Mariasiu F (2013) Consumers' attitudes related to biofuel use in transportation. Int Rev Manag Mark 3:1–9
51 Pagiaslis A, KrystallisKrontalis A (2014) Green consumption behavior antecedents: environmental concern, knowledge, and beliefs. Psychol Mark 31(5):335–348
52. Lanzini P, Testa F, Iraldo F (2016) Factors affecting drivers' willingness to pay for biofuels: the case of Italy. J Clean Prod 112:2684–2692
53. Simons L, Engelmann L, Arning K, Ziefle M (2021) Two sides of the same coin—explaining the acceptance of CO_2-based fuels for aviation using PLS-SEM by considering the production and product evaluation. Front Energy Res 9:742109
54 Arning K, Linzenich A, Engelmann L, Ziefle M (2021) More green or less black? How benefit perceptions of CO_2 reductions vs. fossil resource savings shape the acceptance of CO_2-based fuels and their conversion technology. Energy Climate Change 2:100025
55. Bask A, Halme M, Kallio M, Kuula M (2020) Business students' value priorities and attitudes towards sustainable development. J Clean Prod 264:121711
56. Jansson J, Marell A, Nordlund A (2011) Exploring consumer adoption of a high involvement eco-innovation using value-belief-norm theory. J Consum Behav 10(1):51–60
57. Preisendörfer P (1998) Umwelteinstellungen und Freizeitmobilität. Gibt es Effekte des allgemeinen Umweltbewusstseins auf das Verkehrsverhalten? Tourismus J 2(4):441–456
58. Abrahamse W, Steg L, Gifford R, Vlek C (2009) Factors influencing car use for commuting and the intention to reduce it: a question of self-interest or morality? Transp Res F: Traffic Psychol Behav 12(4):317–324
59. Beier G (1999) Kontrollüberzeugungen im Umgang mit Technik. Report Psychologie 24(9):684–693
60. Fazel L (2014) Akzeptanz von Elektromobilität: Entwicklung und Validierung eines Modells unter Berücksichtigung der Nutzungsform des Carsharing. Schriften zum europäischen Management. Springer Gabler, Wiesbaden
61. Steg L (2005) Car use: lust and must instrumental, symbolic and affective motives for car use. Transp Res Part A Policy Pract 39(2–3):147–162
62. Osgood CE, Suci GJ, Tannenbaum PH (1957) The measurement of meaning. The measurement of meaning. Univer. Illinois Press, Urbana
63 Sijtsema SJ, Onwezen MC, Reinders MJ, Dagevos H, Partanen A, Meeusen M (2016) Consumer perception of bio-based products—an exploratory study in 5 European countries. NJAS Wageningen J Life Sci 77:61
64. Cacciatore MA, Scheufele DA, Shaw BR (2012) Labeling renewable energies: how the language surrounding biofuels can influence its public acceptance. Energy Policy 51:673–682

Publisher's Note