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Between financial, environmental and health concerns: the role of risk perceptions in modeling efuel acceptance

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The transition towards sustainable and defossilized mobility systems relies on public perception and acceptance of innovations like efuels. Understanding the role of risk perceptions and their different dimensions in shaping public acceptance is therefore critical for facilitating the introduction of efuels into mobility systems. A quantitative survey was conducted among a representative sample of 517 German participants to assess their risk perceptions and acceptance of efuels. A Structural Equation Modeling (SEM) approach was employed to analyze the relationships between cognitive, affective, and domain-specific risk perceptions (health, environmental, and financial) and public acceptance of efuels. The analysis revealed low levels of both cognitive and affective risk perceptions as well as positive acceptance levels for efuels. Financial risk perception was more pronounced than health or environmental risk perceptions. Affective and cognitive risk perceptions were found to negatively impact acceptance, with cognitive risk perception showing a stronger influence. Environmental risk perception was negatively associated with acceptance, while health and financial risks showed no significant association. The findings suggest that while efuels are generally accepted, financial and environmental concerns might hinder widespread adoption. Addressing these concerns through targeted communication strategies that combine cognitive (economic, environmental) and affective (health) dimensions is essential for a socially accepted design of sustainable mobility systems.

KEYWORDS

risk perception, acceptance, structural equation model, affective, cognitive, environment, finance, survey

1 Introduction

The transition to a sustainable and defossilized mobility system relies not only on the technical and economic feasibility of innovations like efuels but also on public acceptance. Acceptance is a critical factor for the successful adoption of innovations like efuels. Despite their potential environmental benefits, public concerns regarding perceived risks can hinder the implementation and rollout of sustainable innovations. For instance, protests against renewable energy projects (Eichenauer and Gailing, 2022), low-carbon energy projects (Temper et al., 2020), and wind turbines (Zilles and Marg, 2023) illustrate how public concerns in terms of perceived risks can impede the sustainable energy transition.

Understanding risk perception is, therefore, essential, as it significantly shapes public acceptance and behavioral intentions (Huijts et al., 2012). Risk perception, which encompasses cognitive, affective, and domain-specific subjective evaluations of potential hazards, can influence whether individuals endorse or reject new technologies (Arning et al., 2020). In the context of efuels, understanding and addressing public perception and concerns early in the development process is critical to mitigating potential barriers to acceptance (Linzenich et al., 2023). A deeper understanding of the relationship between risk perception and acceptance can guide the development of strategies that not only address public concerns but also promote informed decision-making.

This study focuses on the perception and acceptance of efuels as one solution to defossilize the mobility sector. By examining the relationship between risk perception and acceptance, we aim to provide insights into the factors influencing public attitudes toward efuels. Specifically, the study investigates cognitive, affective, and domain-specific dimensions of risk perception and their role in shaping acceptance. These findings can help guide both development and communication strategies to promote informed decision-making in the public about efuels as part of a sustainable mobility transition.

2 Background

2.1 Efuels in the mobility transition

The development and production of efuels offer a promising pathway to decarbonizing the transport sector, particularly for applications where electrification remains challenging. When produced with renewable energy, efuels can achieve carbon-neutral emissions, positioning them as a sustainable alternative to fossil fuels (Brynolf et al., 2022). The production of Fischer-Tropsch fuel, dimethyl ether, and methanol via synthesing carbon monoxide (CO) and hydrogen (H_2) to produce syngas are established routes of efuel production (Dieterich et al., 2020). The carbon dioxide (CO_2) needed as a carbon source is captured via Direct Air Capture (DAC) (Ababneh and Hameed, 2022) or separated at a carbon-intensive point source (e.g., cement plant)—for example via membrane or adsorbent utilization—to be subsequently transported in a compressed state (e.g., via pipeline) to a site where it is utilized or further processed (Hasan et al., 2015).

Efuels have potential applications across multiple sectors. In aviation, responsible for 920 megatons of CO_2 emissions in 2019 (Klenner et al., 2024), efuels can enable more climate-friendly passenger and freight transport (Lehtveer et al., 2019). Similarly, for maritime transport, efuels offer an alternative to technologies like fuel cells, which face significant development challenges (Horvath et al., 2018). In road traffic, where cars (447 megatons of CO_2) and heavy-duty trucks (208 megatons of CO_2) are the largest contributors to emissions (Eurostat, 2024), efuels could serve as a bridge technology, particularly for existing internal combustion engines. However, production characteristics such as the complexity of manufacturing steps, costs, and currently low fuel yields represent barriers in the scale-up of efuel production (Peixoto et al., 2023). Factors influencing the price of efuels include the production site (e.g., proximity to carbon capture facilities or renewable energy sources) and the cost of electricity generation (Runge et al., 2023). Consequently, efuels are significantly more expensive than conventional fossil fuels (Colelli et al., 2023). Bridging this price gap requires the implementation of adequate policy frameworks that support the rollout of sustainable fuel alternatives (Skov and Schneider, 2022).

In the long term, Danieli et al. (2023) estimate that under current policies, efuels may become more cost-effective than electric vehicles as an alternative mode of sustainable road transport. Additionally, Styring et al. (2021) highlight that electric vehicles are often associated with high initial purchase costs, suggesting that efuels can serve as a bridging technology, particularly for low-income earners.

A further advantage of efuels is their compatibility with existing infrastructure, such as fueling stations, and their ability to be used in current internal combustion engines without significant modifications (Richter et al., 2024). These characteristics make efuels a potential and practical solution in transitioning to more sustainable mobility systems.

2.2 Risk perception and acceptance

The transition to a sustainable and defossilized mobility system depends heavily on public acceptance of innovations like efuels. *Acceptance*, defined as the public's approval or endorsement of the development, implementation, and use of new technologies (Flynn, 2007), is a multifaceted construct with positive (e.g., support) and negative (e.g., protest) expressions (Schweizer-Ries, 2008). The diffusion of sustainable energy systems in the past demonstrated that the public's response to such developments was often characterized by protests, e.g., against the construction of wind farms (Devine-Wright, 2008), or the reluctance to adopt more sustainable drive types like electric vehicles (Kumar and Alok, 2020). Protests and boycotts, in turn, represent negative manifestations of acceptance. According to the conceptualization of Wüstenhagen et al. (2007), acceptance encompasses three dimensions: the first is sociopolitical acceptance, which concerns the general public's approval of a technology. The second is community acceptance, which is based on the approval of local stakeholders of a technology's fairness, justice, and trust. The third is market acceptance, which is the consumer's or industry's willingness to adopt or invest in a technology. The present study focuses on the overlap of sociopolitical and market/consumer acceptance of efuels.

Risk perception plays a critical role in shaping acceptance. Unlike objective risk, which can be quantified in measurable data and is defined as probability x severity of consequences (Aven et al., 2011), risk perception refers to individuals' beliefs, attitudes, judgments, and feelings toward risk, incorporating the wider social and cultural values, as well as outlook that people adopt toward hazards (Bodemer and Gaissmaier, 2015). Cognitive risk perception involves analytical assessments, such as probability and severity of consequences, whereas affective risk perception reflects emotional and intuitive responses to perceived risks (Slovic et al., 2004). Dual-process models of risk perception suggest that these cognitive and affective pathways often interact, with affective responses influencing cognitive evaluations through heuristics, such as the affect heuristic (Finucane et al., 2000). The affect heuristic (Finucane et al., 2000) describes how these affective judgments, driven by emotions and personal feelings, exert a "coloring" effect on cognitive evaluations, leading individuals to make decisions rapidly and effectively by relying on their current mood or "gut feelings". In addition to these dimensions, domain-specific risk perceptions—such as concerns about environmental, financial, and health-related impacts—are also key factors influencing acceptance. For example, concerns about environmental harm or economic feasibility can shape public attitudes toward new technologies (Arning et al., 2020). Understanding how these various dimensions of risk perception interact is essential for predicting acceptance and designing effective communication strategies to address public concerns.

Theoretical models of acceptance (e.g., Huijts et al., 2012) posit that the acceptance of new technologies like efuels is closely linked to perceived risks. These models suggest that higher perceived risks lead to lower acceptance, emphasizing the importance of understanding the origin and effects of risk perceptions. Understanding the multidimensional risk perception construct and its relationship with acceptance is crucial for understanding public perception of efuels as one sustainable approach in the mobility transition. The following section therefore provides an overview of the current empirical state of research on risk perception and acceptance of efuels.

2.3 Empirical state of the art on efuel risk perception and acceptance

Recent research has investigated public acceptance of alternative fuels, finding generally positive acceptance levels, particularly due to their perceived environmental benefits across various applications, including aviation (Simons et al., 2021), marine transport (Bilgili, 2023), and both public and private transport (Jansson and Rezvani, 2019; Linzenich et al., 2019). In the private transport sector, acceptance has been linked to environmental advantages as well as economic benefits (Chaiyapa et al., 2018) and technical advantages over electric vehicles, such as greater range and compatibility with existing infrastructure (Kowalska-Pyzalska et al., 2022; Linzenich et al., 2019). Established factors like efficiency and perceived usefulness have also been identified as significant predictors of acceptance (Pfoser et al., 2018).

These include infrastructure challenges, such as the location, number, and size of refueling stations, as well as the necessity for building new infrastructure (Hardman et al., 2017). Additional barriers include financial concerns, and lack of information (Steenberghen and Lopez, 2008). While the risk perception of alternative fuels is generally lower than that of conventional fuels (Engelmann et al., 2020), they are still associated with environmental and health risks (Winden et al., 2014; Bonaiuto et al., 2024).

Most empirical studies to date have examined alternative fuels at a generalized level, often grouping them without distinguishing between specific fuel or drive types (Bilgili, 2023; Kowalska-Pyzalska et al., 2022; Linzenich et al., 2019; Mohammed et al., 2020). Some research has focused on individual alternative fuel types, such as carbon dioxide-based fuels (Arning et al., 2023; Engelmann et al., 2020) or biofuels (Bonaiuto et al., 2024; Chaiyapa et al., 2018). However, specific insights into the risk perception and acceptance of efuels remain sparse, and a detailed understanding of affective and cognitive evaluation dimensions (i.e., risks, but also benefits) as well as their impact on the acceptance of efuels is missing.

2.4 Research model and hypotheses

To investigate the relationship between risk perception dimensions, i.e. perceived affective and cognitive risks, domain-specific risk perceptions related to health, environmental, and financial effects of efuels as a sustainable fuel solution and acceptance of efuels, the following research model and specific research hypotheses were proposed (Figure 1):

Relationship between affective risk perception, cognitive risk perception, and acceptance.

H1.1: Affective risk perception is positively associated with cognitive risk perception.

H1.2: Affective risk perception is negatively associated with acceptance.

H1.3: Cognitive risk perception is negatively associated with acceptance.

Relationship between cognitive risk perception and perceptions of domain-specific risk effects.

H2.1: Cognitive risk perception is positively associated with health risk perception.

H2.2: Cognitive risk perception is positively associated with financial risk perception.

H2.3: Cognitive risk perception is positively associated with environmental risk perception.

Relationship between affective risk perception on domain-specific risk perceptions.

H3.1: Affective risk perception is positively associated with health risk perception.

H3.2: Affective risk perception is positively associated with financial risk perception.

H3.3: Affective risk perception is positively associated with environmental risk perception.

Relationship between domain-specific risk perceptions and acceptance.

H4.1: Health risk perception is negatively associated with acceptance.

H4.2: Financial risk perception is negatively associated with acceptance.

H4.3: Environmental risk perception is negatively associated with acceptance.

3 Materials and methods

This section provides an overview of the measurement instrument, data collection and preparation procedures, and the final sample selection. In addition, it provides an overview of the statistical method of analysis used, the Partial Least Squares Structural Equation Modeling (PLS-SEM).

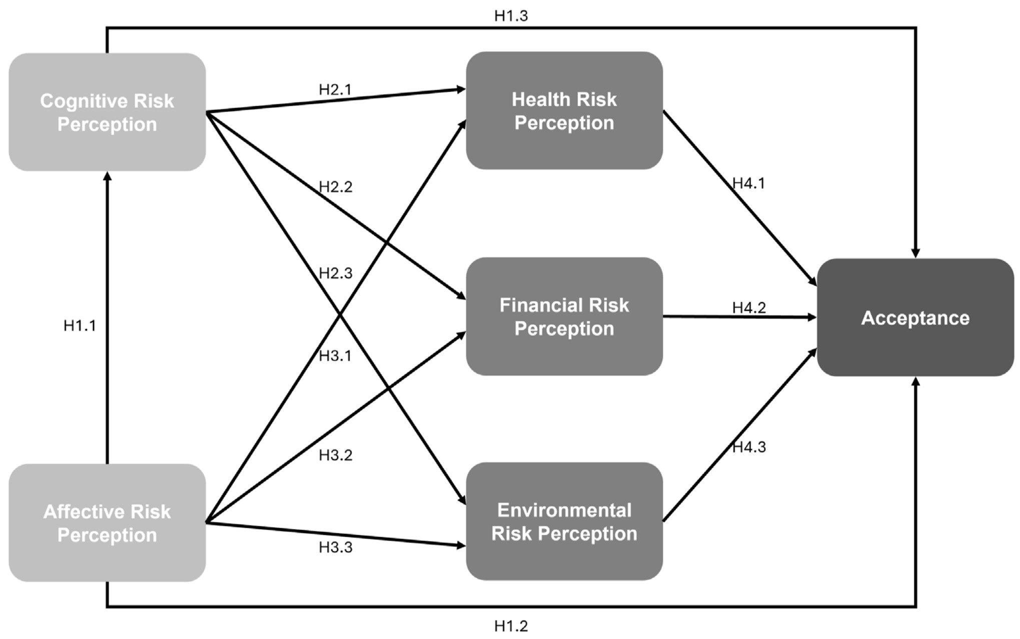

FIGURE 1
Research model with hypothesized relationships between risk perception dimensions and acceptance of efuels.

3.1 Questionnaire

A quantitative online questionnaire survey, created using Qualtrics survey software, was employed to assess risk perceptions and acceptance towards efuels and individual factors among German laypersons. The questionnaire aimed to assess a representative sample of people living in Germany above the age of 16. Data assessment was carried out in April 2023 via a market research institute. The questionnaire received approval from the Ethics Committee of the "Empirical Human Sciences" department of the Faculty of Humanities at RWTH Aachen University.

The following provides a general overview of the survey structure and detailed information on the specific items that were included in the survey.

The introductory section of the questionnaire began with a confirmation of the participant's willingness to provide further responses and then proceeded to request socio-demographic information, ensuring the representativeness of the sample, including gender, age, place of residence, and estimated income. Additionally, participants were asked to indicate their highest level of education, which was subsequently categorized according to the International Standard Classification of Education (ISCED) (UNESCO Institute for Statistics, 2012). This was followed by questions relating to the participant's mobility habits, with a particular focus on their use of cars, and included queries regarding their ownership of cars, vehicle utilization (frequency of usage and average distance per year), and the type of propulsion system mainly employed.

The main part started with an introductory text on efuels, which was developed with technical experts of the RWTH Aachen University Excellence Cluster The Fuel Science Center (FSC) to ensure factual correctness and comprehensibility.

After the introductory text, different dimensions of risk perception and acceptance ratings were assessed. To prevent the occurrence of a central tendency bias and ensure comparability, all items of the specific ratings were subjected to measurement on a six-point Likert scale or on a six-point semantic differential, ranging from low risk or acceptance (coded with 1) to high risk or acceptance (coded with 6). Affective risk perceptions [Cronbach's $\alpha = .93$, adapted from Walpole and Wilson (2021)] were measured with three items on a six-point Likert scale (e.g., participants were asked to rate "How worried are you, if at all, about efuels?"). In contrast, semantic differentials were applied to measure cognitive risk perceptions [5 items, $\alpha = .88$, adapted from Arning et al. (2023)] and acceptance ratings [3 items, $\alpha = .94$, adapted from Engelmann et al. (2020)] of efuels (e.g., from "conventional" or "meaningless", to "innovative" or "meaningful"). Furthermore, perceived risk effect ratings based on the susceptibility items of Walpole and Wilson (2020) and adapted for the specific survey context, regarding perceived risk effects associated with efuels on health (2 items, $\alpha = .89$), finance (3 items, $\alpha = .8$), and the environment (3 items, $\alpha = .89$) were assessed on a Likert-scale, addressing the suspected impact and severity of risks related to the introduction of efuels. Additionally, one item of the financial and environmental risk perception was assessed on a semantic differential. Table 1 provides a detailed overview of the individual item formulations.

The items were presented in randomized order to avoid sequence effects. Some items were set up in negative coding to avoid answering biases and were recoded for statistical analysis. For further statistical analysis, mean scores were built for each risk perception dimension and acceptance respectively. The response time to fully complete the survey, based on the median, was on average Mdn = 16:45 min (SD = 15:50 min).

TABLE 1 PLS model quality measurement results (RP: Risk perception, NOI: Number of items; AVE: Average variance extracted, CR: composite reliability, CRA: Cronbach's alpha), items, and descriptive statistics (M: Mean, SD: Standard deviation) for all items.

Construct	NOI	AVE	CR	CRA	Items	Factor loadings	M	SD
Cognitive RP	5	0.67	0.88	0.88	*Cognitive Risk Perception Index*	-	3.1	1.2
					How do you perceive efuels: uncontrollable - controllable	0.85	2.9	1.3
					How do you perceive efuels: underdeveloped - developed	0.77	3.7	1.4
					How do you perceive efuels: short-lived - future-proof	0.87	3.1	1.5
					How do you perceive efuels: conventional - innovative	0.78	2.7	1.3
					How do you perceive efuels: not understandable - understandable	0.82	3.1	1.5
Affective RP	3	0.87	0.93	0.93	*Affective Risk Perception Index*	-	2.6	1.3
					How worried are you, if at all, about efuels?	0.95	2.7	1.4
					How concerned are you, if at all, about efuels?	0.95	2.7	1.4
					How afraid, if at all, are you of efuels?	0.91	2.5	1.4
Health RP	2	0.90	0.89	0.89	*Health Risk Perception Index*	-	2.8	1.2
					How likely do you think efuels have a negative impact on: your health or your family's health?	0.95	2.8	1.3
					How severely will the introduction of efuels affect: your health or your family's health?	0.94	2.7	1.3
Financial RP	3	0.70	0.79	0.79	*Finance Risk Perception Index*	-	3.6	1.2
					How likely do you think efuels have a negative impact on: your financial situation?	0.86	3.4	1.4
					How severely will the introduction of efuels affect: your financial losses?	0.86	3.4	1.4
					How do you perceive efuels: expensive - cheap	0.78	4.1	1.4
Environmental RP	3	0.82	0.89	0.89	*Environmental Risk Perception Index*	-	3.1	1.2
					How likely do you think efuels have a negative impact on: the environment?	0.91	3.2	1.3
					How severely will the introduction of efuels affect: the environment?	0.91	3.1	1.3
					How do you perceive efuels: environmentally harmful - environmentally friendly	0.89	3.0	1.4

(Continued on the following page)

TABLE 1 (*Continued*) PLS model quality measurement results (RP: Risk perception, NOI: Number of items; AVE: Average variance extracted, CR: composite reliability, CRA: Cronbach's alpha), items, and descriptive statistics (M: Mean, SD: Standard deviation) for all items.

Construct	NOI	AVE	CR	CRA	Items	Factor loadings	M	SD
Acceptance	3	0.89	0.94	0.94	*Acceptance Index*	-	4.0	1.4
					How do you perceive efuels: meaningless - meaningful	0.95	3.9	1.5
					How do you perceive efuels: useless - useful	0.94	4.1	1.5
					How do you perceive efuels: unacceptable - acceptable	0.94	4.0	1.5

3.2 Sample

Following the completion of data cleaning procedures, targeting speeders, and invalid response patterns, the total sample size consisted of N = 517 datasets (original data sample size N = 1,108). The 517 valid datasets demonstrated the targeted representativeness of the German public according to gender, age, area of residence, and educational level. In particular, 47.8% of respondents described themselves as male (n = 247), 52.2% as female (n = 270), no participant indicated a non-binary gender identity. The participants' mean age was M = 48.81 years (SD = 14.5), with an age range from 16 to 86 years. According to the ISCED, the majority of participants (n = 299, 57.8%) reported a low educational attainment level, 23.8% a high (n = 123), and 18.4% a medium level of educational attainment (n = 95). Regarding income estimation, the majority of the sample (n = 224, 43.3%) reported their income to fall within the range of 1,050 to 3,000. In terms of geographical distribution, the majority of participants reported to live in suburban areas (n = 224, 43.3%), followed by those residing in urban centers (n = 144, 27.9%), and rural areas (n = 149, 28.8%). Even though sample did not exclusively comprise individuals who use automobiles as a primary mobility resource, a significant majority either possessed a car (n = 352, 68.1%) or had consistent access to one (n = 100, 19.4%). Furthermore, 62.9% reported using a car on a weekly to daily basis (n = 325). Among those who utilized cars within the sample, over 90% predominantly relied on fossil fuels (gasoline and diesel) as their primary fuel source, with only a minority opting for electric vehicles (EVs) (3%) or hybrid models (4%).

3.3 Statistical analysis

We employed Structural Equation Modeling (SEM) to explore the complex relationships among affective, cognitive, and domain-specific risk and benefit perceptions as well as acceptance of efuels. SEM is a versatile analytical framework that combines techniques like regression and path analysis to investigate both direct and indirect relationships between constructs (Pearl, 2012). SEM relies on the researcher's causal assumptions, which are grounded in theory, the research design employed, and logical reasoning (Bollen and Pearl, 2013). It is a powerful tool for translating qualitative causal assumptions into quantitative causal inferences and statistical metrics that provide insight into the goodness of fit of the structural specifications (Pearl, 2012).

For this study, we chose Partial Least Squares SEM (PLS-SEM) due to its suitability for exploratory research questions and its advantages over covariance-based SEM. PLS-SEM is particularly robust for analyzing models with evolving theoretical underpinnings and non-normal data distributions (Hair et al., 2021). Additionally, its lower sample size requirements and focus on predictive accuracy were reasons for choosing it as an analysis tool for our data set of 517 participants. By allowing simultaneous analysis of interdependent relationships and providing tools for assessing measurement reliability and validity (e.g., composite reliability, AVE), PLS-SEM enabled us to effectively model the interplay of risk perceptions and acceptance of efuels. The dual-level structure of PLS-SEM, encompassing measurement, and structural models, ensured a comprehensive evaluation of both construct reliability and hypothesized relationships. Its predictive focus further aligned with the study's goal of identifying key drivers of efuel acceptance, such as cognitive and affective risk perceptions.

Before analysis, the dataset underwent rigorous cleaning procedures to ensure data quality. Participants who exhibited speeding behavior by completing the survey in less than one-third of the median processing time were excluded. Additionally, straightlining (e.g., selecting the same response for all items) and invalid answering patterns in trap questions designed to assess attentiveness were identified and removed. After the data cleaning process, the total sample size was adjusted from N = 1,108 to N = 517 datasets.

4 Results

4.1 Risk perception and acceptance of efuels

The analysis of the construct *affective risk* indicates that people did not show heightened levels of risk perception, as indicated by $M = 2.6$ ($SD = 1.3$; see Figure 2), a mean value significantly differing from 3.5, the mid-point of the scale ($t_{516} = -15.09$, $p < 0.001$). For *cognitive risk*, a similar, rather low level of cognitive assessment of efuel risk was measured ($M = 3.1$, $SD = 1.2$; $t_{516} = -7.63$, $p < 0.001$).

For the perception of domain-specific risk effects we find that while *financial risk perception* was slightly elevated ($M = 3.6$, $SD =$

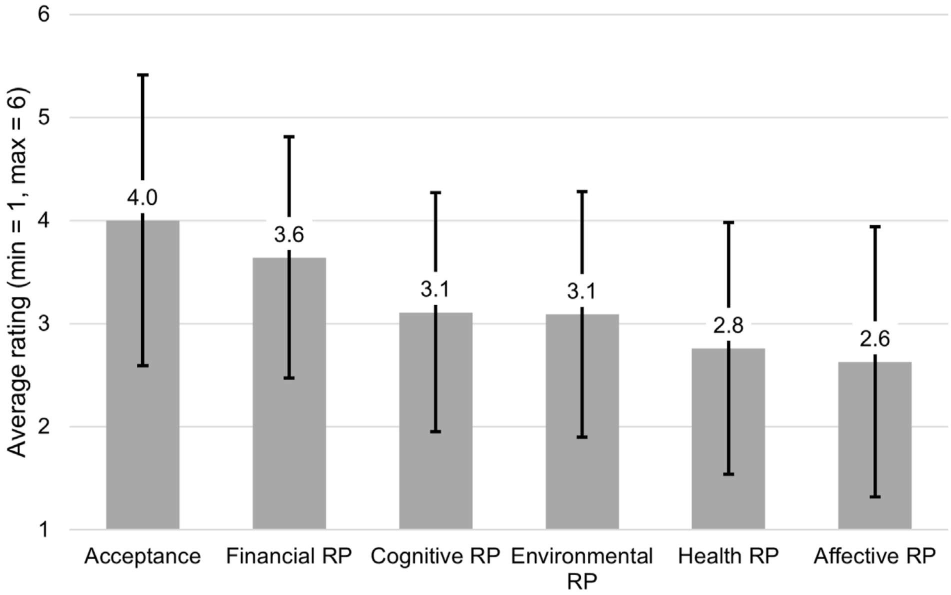

FIGURE 2
Mean values (with standard deviations) of risk perception dimensions and acceptance of efuels. RP = risk perception.

1.2; $t_{516} = 2.71$, $p = 0.007$), *environmental risk perception* was rather low ($M = 3.1$, $SD = 1.2$, $t_{516} = -7.72$, $p < 0.001$) and significantly lower than *financial risk perception* ($t_{516} = 11.22$, $p < 0.001$). In comparison to that, respondents reported an even lower *health risk perception* ($M = 2.8$, $SD = 1.2$, $t_{516} = -13.76$, $p < 0.001$), which was significantly lower than *environmental risk perception* ($t_{516} = -8.36$, $p < 0.001$).

The analysis of the construct *acceptance of efuels*–the dependent variable of the structural PLS model–indicates that respondents rather accept efuels for use in road traffic, as is illustrated by $M = 4.0$ ($SD = 1.4$) and confirmed by the mean value significantly differing from the mid-point of the used scale ($t_{516} = 7.97$, $p < 0.001$).

Summing up, the descriptive analysis revealed that affective and cognitive risk perceptions of efuels were not increased. Financial risk perception was slightly elevated, while environmental and health risk perceptions were rejected, i.e., did not raise concerns about negative environmental or health effects. Overall, the use of efuels in road traffic was perceived as acceptable.

4.2 PLS model evaluation

4.2.1 Evaluation of the measurement model

We tested the PLS measurement model following the procedure recommended by Hair et al. (2019) to demonstrate that all assessed constructs and items had satisfactory measurement properties, i.e., were reliable and valid indicators of the constructs in the PLS model.

Measurement model loadings, significance, and indicator reliability: To analyze if all indicators (items) contributed to the respective factor (construct), item loadings were analyzed. Items with a contribution below 0.6 were removed from the statistical analysis. In the final model, all outer loadings between the indicators (items) and the factor (construct) exceeded the recommended minimum value of 0.6 (Hair et al., 2021) for empirical field research and were significant ($p < 0.05$) (Table 1), with factor loadings ranging from 0.774 to 0.953. Thus, satisfyingly high levels of indicator (item) reliability were achieved for all assessed reflective constructs.

Internal consistency reliability: The internal reliability (as indicated by Cronbach's alpha, CRA) of all constructs was found to be above the recommended value of 0.7 (Hair et al., 2019) (Table 2, CRA). However, it should be noted that Cronbach's alpha is sensitive to the number of items in a scale and tends to underestimate internal consistency reliability. Therefore, the composite reliability was also calculated. Therefore, the composite reliability (CR) was also calculated. The composite CR of the different measures was > .79 and exceeded the recommended threshold value of 0.7 (Table 1, CR).

Convergent validity: The convergent validity of the construct was evaluated using three specific measures. These measures were employed to assess the extent to which all indicators collectively explain a significant amount of variance. Firstly, it was necessary for the factor loadings for each indicator to be significant and to exceed 0.7. Secondly, each construct's composite reliability (CR) was required to exceed 0.7. Thirdly, the average variance extracted (AVE) for each construct was expected to be above 0.5, indicating the ratio of explained to unexplained variance. As illustrated in Table 1, the AVE values exhibited a range of 0.67–0.89. The attainment of these thresholds across all criteria proves the convergent validity of our model.

Discriminant validity: The discriminant validity of the constructs within the measurement model was assessed to confirm that they were sufficiently distinct. This analysis is important for accurately interpreting relationships between different constructs. Two methods were employed to establish discriminant validity. The first was the Fornell-Larcker Criterion (FLC), which involved comparing the square root of the Average Variance Extracted (AVE) with the correlations among constructs. The results indicated that all inter-construct correlations were lower than the FLC, thereby affirming discriminant validity. The Heterotrait-Monotrait Ratio

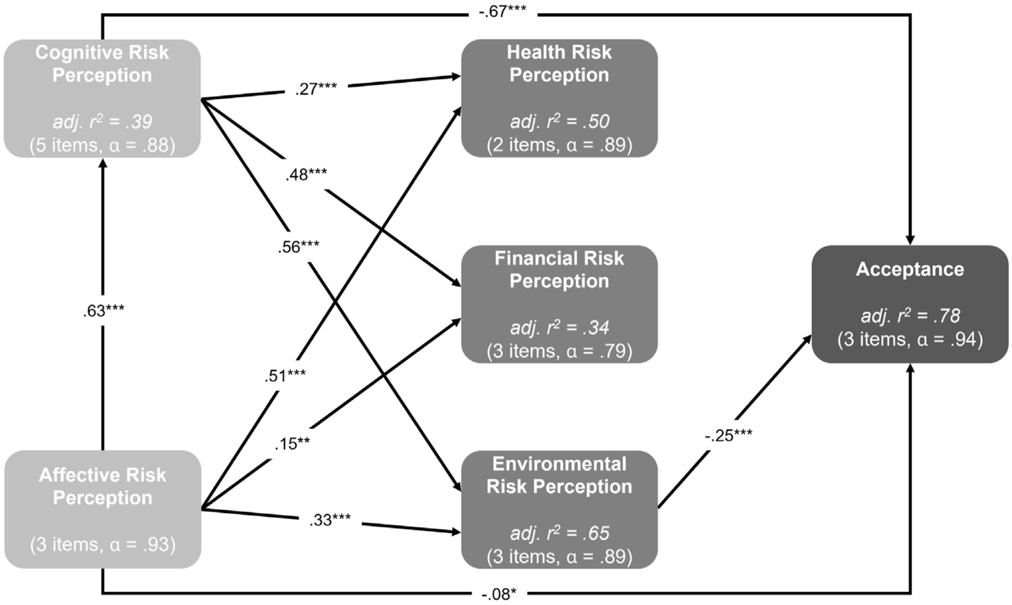

FIGURE 3
PLS-SEM structural modeling results with path coefficients for risk perceptions and efuel acceptance (*p < 0.05,**p < 0.01,***p < 0.001).

(HTMT) was also applied as a secondary measure. The HTMT values ranged from 0.53 to 0.86, remaining below the threshold of 0.9, indicating that our measurement model not only met the criteria for discriminant validity but also exhibited adequate reliability and convergent validity, thereby ensuring the robustness of the analysis of construct relationships.

4.2.2 Evaluation of the path model

Following the evaluation of the measurement model, the hypothesized relationships were tested in the structural model. Only statistically significant paths are depicted in the path model (Figure 3). The significance levels were estimated using t-statistics derived from a bootstrapping method with 2000 sub-samples. To assess the model's overall predictive power, the coefficient of determination (R^2) was calculated (Hair et al., 2021). The structural path model accounted for 78% of the variance. This indicates that the evaluated latent variables (affective, cognitive, health, financial, and environmental risk perceptions) collectively explained 78% of variance in acceptance. The explained variance for the other risk perception constructs in the path model is detailed in the structural model (Figure 3).

The structural model showed a significant strong positive association between affective and cognitive risk perception ($\beta = .63$, $p < 0.001$, H1.1 confirmed). This indicated that elevated levels of affective risk perception were associated with elevated levels of cognitive risk perception. Affective risk perception was negatively associated with acceptance ($\beta = -.08$, $p < 0.05$), indicating that increased affective risk perception was associated with lower acceptance levels. Cognitive risk perception was also found to have a strong negative relationship with acceptance ($\beta = -.67$, $p < 0.001$, H1.3 confirmed), indicating that higher cognitive risk perception was associated with decreased acceptance.

Cognitive risk perception was found to be positively associated with health risk perception ($\beta = .27$, $p < 0.001$, H2.1 confirmed), financial risk perception ($\beta = .48$, $p < 0.001$, H2.2 confirmed), and environmental risk perception ($\beta = .56$, $p < 0.001$, H2.3 confirmed). This indicated that higher cognitive risk perception was associated with increased perceptions of health, financial, and environmental risks.

Affective risk perception was found to be positively associated with health risk perception ($\beta = .51$, $p < 0.001$, H3.1 confirmed), financial risk perception ($\beta = .15$, $p < 0.01$, H3.2 confirmed), and environmental risk perception ($\beta = .33$, $p < 0.001$, H3.3 confirmed). This indicated that elevated levels of affective risk perception were associated with elevated levels of health, financial, and environmental risk perceptions.

Regarding the relationship between domain-specific risk perceptions and acceptance, health risk perception was not associated with acceptance (n.s., H4.1 rejected). The same applied to financial risk perception, which did not show a significant relationship with acceptance (n.s., H4.2 rejected). Environmental risk perception was negatively associated with acceptance ($\beta = -.25$, $p < 0.01$, H4.3 confirmed), suggesting that higher environmental risk perception resulted in decreased acceptance.

5 Discussion

5.1 Social perception and acceptance of efuels

Despite the varying levels of risk perception, our study found that acceptance of efuel is relatively high, which reflects a positive public attitude–an important prerequisite of technology implementation. This finding aligns with other studies on the topic of alternative fuels in general (e.g., (Jansson and Rezvani, 2019; Pfoser et al., 2018), and studies on efuel in particular (Offermann-van Heek et al., 2020; Arning et al., 2023).

Both the *affective and the cognitive perception* of the risk of efuels are relatively low, which suggests a positive starting point for a public reaction towards this product. The relatively low levels in both affective and cognitive domains suggest that the public does not strongly associate efuels with significant concerns or threats. This is in line with findings from other studies, where cognitive and affective risk perceptions for efuels were not highly elevated (Rößler et al., 2024; Engelmann et al., 2020). The direct and negative association between affective and cognitive risk perceptions in the PLS model (see Figure 3) indicates that affective perceptions influence cognitive evaluation pathways. This suggests the effect of the affect heuristic, as described by Finucane et al. (2000), which refers to the tendency for individuals to rely on their emotional responses when assessing risks and benefits. Emotions, especially negative ones, shape the way people process and interpret risk-related information, leading to judgments that emphasize potential dangers. In this way, negative affect "colors" cognitive evaluations, causing people to perceive risks as higher than they might objectively be, thereby influencing their decisions and behaviors towards greater caution or avoidance. In turn, positive emotions tend to reduce cognitive perceptions. When the public perceives efuels as part of a broader movement towards sustainability, their positive affect towards this environmental goal can lower their perceived cognitive risks of the technology. This underscores the importance of considering and integrating both affective and cognitive dimensions into risk perception studies and the design of communication strategies.

In terms of *domain-specific risk perceptions*—health, environment, and finance—we found interesting distinctions. Health-related risk perceptions, such as concerns for personal or family health, are notably lower than environmental risk perceptions. This could indicate broader societal confidence in the safety of efuels from a health perspective, perhaps due to the expectation that they will not pose significant health hazards during development and implementation. On the other hand, environmental risk perceptions are higher, which may reflect heightened public awareness of environmental issues and concerns over potential negative ecological impacts of efuel production or use (Berryessa and Caplan, 2020; Arning et al., 2023). These findings suggest that environmentally conscious individuals may be more cautious about efuels, influencing their acceptance primarily through environmental concerns rather than health concerns.

Interestingly, financial risk perception, although moderate, is more pronounced compared to health-related risk. This emphasizes the importance of cost-related factors in the public's evaluation of efuels. Financial considerations, such as the perceived economic feasibility and cost-efficiency of using efuels, appear to play a significant role in shaping public attitudes [e.g. Linzenich et al. (2019)]. This finding is consistent with previous studies that indicate financial risk perceptions can often outweigh other types of risks when it comes to public acceptance of new technologies (Pfoser et al., 2018). In the context of efuels, public perceptions may be shaped more by concerns over affordability and market feasibility rather than direct risks to health or the environment. The finding that financial risk perception is the most pronounced domain-specific risk highlights the need for appropriate measures to facilitate the roll-out of alternative fuel types, i.e., by regulative economic measures (e.g., via preferential tax treatment for these alternatives) and corresponding public communication.

Regarding the influence of cognitive and affective risk perceptions on the *acceptance* of efuels, the evidence supports a stronger influence of cognitive over affective risk perceptions. This aligns with other studies on technology acceptance, which often find that when technologies are perceived as less risky in a cognitive sense—assessed through factors such as economic viability and environmental impact—they are more likely to be accepted by the public [e.g., Huijts et al. (2012); Arning et al. (2020)]. Conversely, the relatively minimal influence of affective risk perception may be attributed to the fact that efuels are not perceived as posing significant emotional or instinctive threats, such as immediate health dangers. This is consistent with the idea that when a technology is perceived as benign or non-threatening on an affective level, its acceptance is more strongly governed by rational, cognitive evaluations (Slovic et al., 2004). Thus, in the case of efuels, where the technology is generally viewed favorably, the affective response appears to play a lesser role in shaping acceptance compared to cognitive evaluations. Therefore, future research and communication strategies should continue focusing on addressing cognitive concerns—especially around environmental impact and financial costs—to further promote the public acceptance of efuels. However, the role of affect should not be entirely discounted, particularly in addressing concerns related to health impacts, where affective responses might develop significant influence. News reports and social media can evoke strong affective reactions, which can shape public perception and amplify concerns, especially regarding health-related risks. Studies show that social media headlines and emotionally charged content can significantly affect how people process and respond to risks (Mousoulidou et al., 2024).

When combining the two dimensions of risk perception (cognitive and affective) with different domains (environmental, financial, and health risk perceptions), distinct patterns emerge in the prediction of acceptance. Cognitive risk perception is most strongly associated with environmental and financial risks, while affective risk perception is primarily linked to health risks, with weaker associations with environmental and minimal connections to financial risks. This suggests that health risks are more strongly related to the affective component of risk perception. In contrast, financial risks are more cognitively processed, relying on rational assessments of costs and benefits. This finding aligns with Loewenstein's "dance of affect and reason" (Loewenstein et al., 2001), where decision-making processes often integrate both emotional (affective) and analytical (cognitive) evaluations.

From a communication and implementation perspective, our findings imply that a strategy addressing efuels should not rely solely on "cold analytics", such as financial reasoning. Instead, it should also incorporate affective elements, particularly when addressing health concerns. For example, communication strategies should emphasize the safety and health benefits of efuels to appeal to emotional responses. This dual approach—balancing emotional reassurance with factual, cognitive information on financial aspects, but also environmental benefits and risks—is crucial for communication and implementing socially accepted fuel innovations.

5.2 Limitations and future research

Our final model allows a detailed analysis of the relationships between affective and cognitive risk perceptions and domain-specific risk perceptions of efuels. However, the primary focus on risks without incorporating the lay perception of benefits presents an imbalanced view. Research has consistently shown that public acceptance of new technologies often hinges on a trade-off between perceived risks and benefits. For example, Offermann-van Heek et al. (2020) highlighted that detailed information about the life cycle of CO_2-based fuels significantly shaped both risk and benefit perceptions, underscoring the importance of clear and balanced communication strategies. Similarly, Linzenich et al. (2019) identified key benefits, such as compatibility with existing fuel infrastructure and reduced reliance on fossil fuels, as pivotal factors influencing acceptance of alternative fuels. To enhance the understanding of efuel acceptance, future models should explicitly consider the role of benefit perceptions, including domain-specific advantages, in direct comparison with risk perceptions. Incorporating benefits such as providing a drop-in solution for existing internal combustion engines, and enabling decarbonization in hard-to-electrify sectors could offer a more comprehensive interpretation of acceptance factors. Balancing these benefits against concerns over environmental, financial, and health risks would align with established frameworks emphasizing the dual role of risk and benefit perceptions in shaping public attitudes (Waters et al., 2023; Huijts et al., 2012; Pfoser et al., 2018).

The sample in our study was representative of the German population based on sociodemographic criteria, such as age, gender, education, and regional distribution. The findings indicated a relatively high level of environmental awareness among participants, which, however, aligns with prior research suggesting that environmental consciousness in Germany is comparably high (German Environment Agency (UBA) and Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV), 2022). This heightened environmental awareness may explain the significant influence of environmental risk perception on acceptance observed in this study. To gain insights into the risk perceptions of individuals with lower environmental awareness, future analyses should focus on individual-level analyses. These approaches could help identify subgroups with different levels of environmental awareness and explore their specific perceptions and attitudes toward efuels.

Additionally, no data was collected in the current study regarding participants' general health status or their attitudes regarding health-related issues. Including this aspect would allow for a deeper understanding of participants' profiles and could enable the analysis of potential moderating impacts of user characteristics on domain-specific risk perception (Arning et al., 2020). The finding that health risk perception did not significantly influence acceptance raises questions about the measurement tools used. Typically, health risks evoke strong emotional responses and should impact acceptance. Future research should refine the measurement of health-related perceptions and explore alternative indicators that may better capture the relationship between health risks and acceptance.

One further limitation of this study lies in the variance explained across the different risk domains. In particular, the variance explained for financial risk perception was significantly lower compared to the other domains. This may be due to the scale employed by Walpole and Wilson (2021), which primarily assessed general perceptions of financial impacts. Future research should consider refining financial risk perception measures to include sector-specific dimensions, such as the projected costs of efuel production, market viability, and long-term affordability. Recent studies, such as Colelli et al. (2023) and Skov and Schneider (2022), highlight the importance of economic policy and technological advancements in shaping these perceptions.

Future studies should further validate this study's findings in different contexts. Since the focus was on efuels, the model should be reproduced and compared with other alternative propulsion technologies, such as electric and bio-based drives. A replication of these results in mobility sectors such as aviation or maritime transport would also allow for a broader understanding of the interplay between risk perception and acceptance. These sectors represent critical areas for decarbonization due to their heavy reliance on fossil fuels and limited electrification options. Additionally, cognitive risk perception ratings may inherently include perceptions of benefits, which could inflate the cognitive evaluation of acceptance. Future research should separate the evaluation of risks and benefits to provide a clearer understanding of how each factor contributes to public acceptance.

Furthermore, cultural contexts play a significant role in shaping perceptions of sustainable technologies. Existing research indicates that risk perception and acceptance vary significantly across countries due to differences in mobility patterns, economic priorities, and societal values (Weber and Hsee, 1998). Comparative studies examining cultural contexts would enhance the generalizability of findings and provide valuable insights for tailoring communication and policy strategies to specific regions.

Finally, cultural contexts play a significant role in shaping perceptions of sustainable technologies. Existing research indicates that risk perception and acceptance vary significantly across countries due to differences in mobility patterns, economic priorities, and societal values (Weber and Hsee, 1998). Comparative studies examining cultural contexts would enhance the generalizability of findings and provide valuable insights for tailoring communication and policy strategies to specific regions.

5.3 Conclusion

In conclusion, our study provides a detailed understanding of how affective and cognitive risk perceptions, as well as domain-specific concerns related to environmental, financial, and health risks, shape the public's acceptance of efuels. Cognitive perceptions, particularly those related to environmental and financial impacts, emerged as significant drivers, indicating that public approval of alternative fuels is closely associated with rational assessments of these factors. Conversely, affective perceptions appear to exert a greater influence in the context of health-related risks, underscoring the necessity for communication strategies that resonate on both an emotional and an analytical level. Future research should build on these findings by including perceptions of benefits and investigating other propulsion technologies to expand the comparative analysis of risk factors influencing acceptance across diverse cultural and mobility contexts. Addressing these elements is critical for developing effective communication and implementation strategies to achieve socially accepted sustainable mobility transformation.

Data availability statement

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

Ethics statement

The studies involving humans were approved by Ethics Committee of the "Empirical Human Sciences" department of the Faculty of Humanities at RWTH Aachen University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

KA: Conceptualization, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing–original draft, Writing–review and editing. JO: Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing–original draft, Writing–review and editing. LE: Data curation, Formal Analysis, Investigation, Methodology, Software, Visualization, Writing–original draft, Writing–review and editing. RG: Formal Analysis, Investigation, Methodology, Writing–original draft, Writing–review and editing. MZ: Funding acquisition, Supervision, Writing–original draft, Writing–review and editing.

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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.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript.The author(s) verify and take full responsibility for the use of generative AI in the preparation of this manuscript. Generative AI was used solely for language polishing to enhance readability and clarity, ensuring that the content remains original and accurate. All content generated by AI was reviewed and validated by the author(s) to maintain the integrity and scientific rigor of the work.

Publisher's note

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