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Original research article

A representative German survey experiment exploring the acceptability of green H_2 storage: Significant links with socio-psychological predictors and targeted information

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ABSTRACT

We examined how socio-psychological predictors link to the acceptability of green hydrogen energy storage systems (H_2ESS) in residential areas and whether targeted information can increase acceptability. A representative German sample ($N = 1004$) completed an experimental online survey. Structural equation modeling (SEM) showed that participants with higher subjective and objective knowledge, as well as greater environmental consciousness, were more accepting. In contrast, participants who experienced stronger feelings of social disconnection (social relatedness frustration) were less accepting. Other indicators of basic psychological need satisfaction and frustration, namely autonomy satisfaction, autonomy frustration and social relatedness satisfaction, did not link to acceptability. Participants were also randomly assigned to one of three experimental conditions or a baseline condition (receiving no information): The experimental conditions consisted of brief text-based interventions on H_2ESS focusing on (1) general information about the functionality and potential applications of H_2ESS, (2) additional information on environmental benefits, or (3) additional information on participation opportunities in the diffusion process of H_2ESS. Participants who received environmental benefits information reported the highest acceptability, followed by those exposed to participation opportunities information, and to a lesser extent those receiving general information, compared to the baseline condition. In open-ended responses, participants most frequently cited environmental sustainability as a reason for support, whereas lack of knowledge and uncertainty were commonly mentioned as reasons for opposition.

1. Introduction

Energy production remains a primary contributor to greenhouse gas emissions and is thus central to climate mitigation efforts [1,2]. The growing share of renewable energy requires more flexible and scalable storage systems, positioning green hydrogen technology at the core of sustainable energy transitions [3]. Hydrogen technology allows to buffer renewable intermittency and stabilize power grids by storing surplus electricity during peak production [4,5]. By 2024, more than 50 governments had adopted national hydrogen strategies, reflecting a coordinated global push to scale up production, distribution, and storage capacities [6]. Current hydrogen storage strategies in Germany primarily focus on large-scale, centralized infrastructure. However, research and pilot projects also explore decentralized applications, including green building- and neighborhood-level hydrogen energy storage systems (H_2ESS) [7,8].

Yet despite the technological momentum, the feasibility of implementing storage systems at scale is not purely a technical matter: New storage systems require social acceptability [9–11]. At the same time, the rapid technological change often exceeds the public's capacity to keep pace and adapt [12]. Although H_2ESS may be physically present in residential contexts, their complexity and reliance on expert knowledge make it difficult for laypeople to understand and relate to them in their everyday life. For unfamiliar technologies such as H_2ESS, this can result in low acceptability levels [13], thereby contributing to delays and project cancellations in the renewable energy sector [14]. Moreover,

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low acceptability can deepen political polarization, simultaneously fueling both pro-environmental and right-wing populist movements [15]. By contrast, individuals who support renewable technologies often express a stronger desire for energy autonomy and a greater willingness to engage in local energy initiatives [16], thus showing a stronger desire to shape their energy future. When considering the acceptability of hydrogen storage in pressurized tanks specifically, individuals generally express support, although safety concerns and misconceptions persist [17].

In this study, we examine public acceptability of H_2ESS that were hypothetically located within a 100-m radius of participants' residence. This residential scenario reflects decentralized hydrogen storage concepts at the building and neighborhood level, where close proximity to individuals makes local public acceptability particularly relevant [18]. Participants evaluated a scenario in which renewable electricity is converted into hydrogen, stored locally, and reconverted into electricity when needed.

We focus on five socio-psychological predictors that potentially link to acceptability of H_2ESS: objective knowledge, subjective knowledge, environmental consciousness, and basic psychological needs, specifically the needs for autonomy and social relatedness. We further test whether general information on the definition and application areas of H_2ESS, information on environmental benefits, or information on participation opportunities in the diffusion process of H_2ESS increase acceptability.

To address these research aims, we applied a mixed-methods design that combined a correlational survey, an experimental information intervention, and open-ended responses on reasons for or against the installation of green H_2ESS. This allows us to test specific hypotheses while also capturing spontaneously expressed arguments. In the following, we introduce the theoretical framework guiding our study, beginning with the dependent variable: acceptability.

1.1. H_2 technology acceptability

Technology acceptability refers to an individual's subjective attitude toward a specific technology [19]. It differs from the often interchangeably used term 'acceptance,' which refers to behavioral responses or intentions that may or may not translate into actual behavior [19–21]. Following prior work distinguishing different dimensions of acceptability (socio-political, market, and community; [9]), we specifically focus on 'community acceptability,' defined as individuals' judgment regarding the installation of H_2ESS in their local environment [17,22].

Relatedly, voting intention captures a concrete behavioral intention toward the installation of a technology and allows for distinguishing between individuals who support, oppose, or remain neutral toward the technology [23,24]. Thus, we additionally asked participants how they would vote in a hypothetical local referendum on the installation of an H_2ESS close to their homes.

1.2. Socio-psychological predictors of acceptability

The Technology Acceptance Framework by Huijts and colleagues (TAF; [20,25,26]) conceptualizes technology acceptability as the outcome of multiple socio-psychological determinants. Rather than attempting to capture all predictors proposed across this and similar technology acceptance models, we adopted a parsimonious approach by selecting variables that represent three complementary socio-psychological pathways to acceptability (see Fig. 1): cognitive evaluations (objective and subjective knowledge), value-based orientations (environmental consciousness), and motivational processes (basic psychological needs).

1.2.1. Objective and subjective knowledge

Objective knowledge (factual knowledge) and subjective knowledge (self-assessed understanding) of hydrogen technologies capture a cognitive basis of acceptability [25]: Acceptability requires at least a minimal understanding of the technology's function and purpose, given the technical complexity and relative unfamiliarity of H_2ESS [26,27].

Individuals who objectively know more about hydrogen technologies, are also more accepting [19,28]. However, individuals with better objective knowledge may also develop more critical views, particularly when they are aware of potential technology risks and limitations. Experts, for example, who highlight technical limitations such as storage inefficiencies or high costs are also more critical [29,30]. Despite this, the general population tends to be broadly accepting of hydrogen technology, despite relatively low levels of objective knowledge [17,31,32].

Individuals who perceive their subjective knowledge to be high also

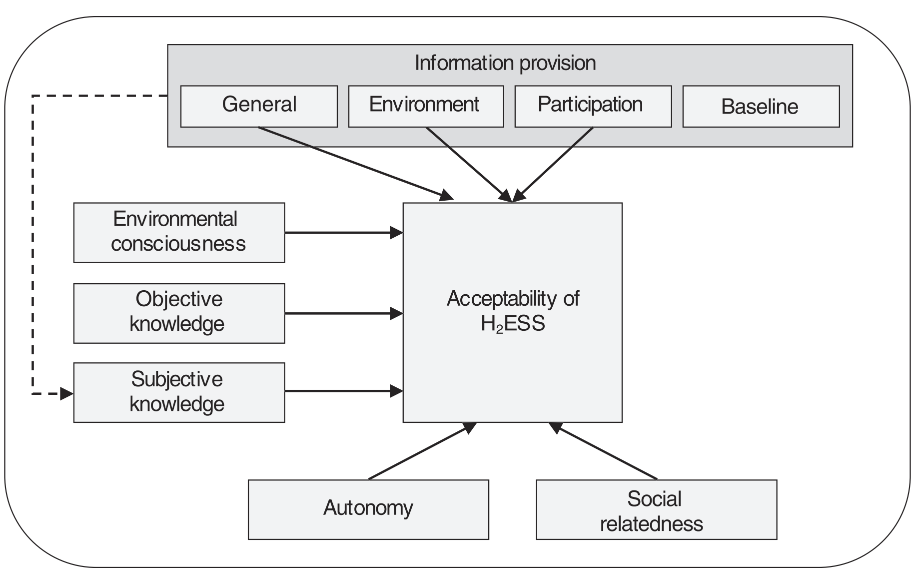

Fig. 1. Conceptual model of hypothesized predictors of H_2ESS acceptability. General = general information about the functionality and potential applications of H_2ESS, Environment = general information and additional information on the environmental benefits of H_2ESS, Participation = general information and additional information about participation opportunities in the diffusion process of H_2ESS, Autonomy = perceived satisfaction and frustration of autonomy (basic psychological need), Social relatedness = perceived satisfaction and frustration of social relatedness (basic psychological need).

have more positive attitudes toward hydrogen technologies across studies [19,25,33,34] and are more likely to support hydrogen technologies [35,36]. This suggests that subjective knowledge links to acceptability, potentially independent of whether the knowledge is accurate.

The present study includes both objective and subjective knowledge to understand their distinct and joint contributions to H_2ESS acceptability. We hypothesize the following:

H1. Participants who objectively know more about hydrogen are more accepting of H_2ESS close to their homes.

H2. Participants who subjectively rate their knowledge of H_2ESS higher are more accepting of H_2ESS close to their homes.

1.2.2. Environmental consciousness

Environmental consciousness captures how individuals think about, feel about, and act toward environmental issues [37,38]. Environmentally conscious individuals are more accepting of hydrogen fuel stations, hydrogen fuel cell vehicles [29], hydrogen fuel cell buses [39], and hydrogen technology in general [40]. Similarly, individuals with a stronger environmental self-identity show higher acceptability both of hydrogen technologies in general and of their local implementation [41]. This pattern also appears in local hydrogen infrastructure contexts, where individuals with stronger climate-related concerns were less likely to reject hydrogen infrastructure projects [22], and individuals with less environmentally oriented attitudes were more likely to oppose local hydrogen storage facilities [35].

We use a validated scale, operationalizing environmental consciousness as a multidimensional construct comprising affective and behavioral components [37] and hypothesize the following:

H3. Participants who are more environmentally conscious are more accepting of H_2ESS close to their homes.

1.2.3. Basic psychological needs

According to Self-Determination Theory, autonomy and social relatedness constitute two of the basic psychological needs, referring to self-determined action and a sense of connection to others [42,43]. Their satisfaction shapes how individuals process and evaluate new information [44]. When psychological needs are fulfilled, individuals' evaluations tend to be more differentiated and less defensive [44,45], which can increase the likelihood that a technology is accepted: Satisfied individuals engage more openly with new information, for example by considering it carefully and weighing it against their existing views, rather than dismissing it quickly or rejecting it categorically [44,45]. Accordingly, individuals who experience higher psychological need satisfaction are more accepting of emerging technologies, including smart learning environments [46,47], health applications [48,49], leisure technologies such as travel tracking [50–52], and hydrogen technologies [53]. More specifically, technologies are more accepted when they support self-directed engagement and perceived control, thereby fostering autonomy [47,49,54,55], and when they are embedded in supportive social contexts, thereby fostering social relatedness [46,49,53,55,56]. Need frustration, in contrast, is linked to maladjustment and defensive responding [42,43]. When psychological needs are frustrated, individuals may become less open toward engaging with unfamiliar technologies and evaluate them more negatively [54–56]. Including basic psychological needs in our conceptual framework allows us to examine whether acceptability of local hydrogen storage is associated not only with cognitive and value-related factors but also with broader motivational conditions.

We thus examine how the psychological needs for autonomy and social relatedness link to the acceptability of H_2ESS. Our hypotheses focus on need satisfaction, while the analyses additionally incorporate need frustration as a conceptually distinct construct. Considering both constructs allows for a more comprehensive test of the underlying motivational processes. We hypothesize the following:

H4. Participants who feel more autonomous in their daily life are more accepting of H_2ESS close to their homes.

H5. Participants who feel more socially related in their daily life are more accepting of H_2ESS close to their homes.

1.3. Information provision on application areas of H_2ESS, environmental benefits, and participation opportunities

Limited knowledge can result in more uncertain and less stable evaluations of emerging energy technologies [57,58], highlighting the importance of effective information provision [57,59]. Information provision is particularly effective in early stages of technology diffusion, when prior knowledge is low and attitudes are not yet firmly established [60]. Providing information increases individuals' subjective knowledge of a technology, which in turn is associated with higher acceptability [61]. Accordingly, information provision increases acceptability by up to 10% for hydrogen export, domestic hydrogen use [62], and hydrogen fueling stations [63]. Beyond information provision itself, the content of the information further shapes acceptability [63,64]:

Providing general information on the functionality and application areas of a technology increases acceptability by enabling individuals to form a basic understanding of the technology [64]. This type of information provides a useful foundation for evaluating the technology, particularly when prior knowledge is limited.

Providing more specific information on environmental benefits also increases the acceptability of hydrogen technologies [64]. Likewise, more positive evaluations of a technology's environmental attributes are associated with stronger intentions to adopt local renewable energy systems [65]. Similarly, communicating environmental benefits increases acceptability in related energy technology contexts such as Carbon Capture and Storage or wind energy [10,66].

Providing information on participation opportunities in renewable energy projects can further increase acceptability, as individuals value co-determination, transparency, and fair profit-sharing [67,68]. Financial compensation schemes, such as payments to residents living near wind farms, likewise increase local acceptability [10,69]. Participation opportunities enhance perceived fairness in decision-making processes, which in turn increases acceptability [10,70,71].

We compare three experimental conditions (general information, general information and additional environmental benefits information, general information and participation opportunities information) to a no-information baseline condition. This design allows us to examine both the effect of providing general information (relative to no information) and the effects of specific information. Because the general information condition was designed solely to increase participants' basic understanding of H_2ESS, we expected its effect on acceptability to be mediated by changes in subjective knowledge. In contrast, the environmental benefits and participation opportunities conditions were intended to influence acceptability through additional evaluative mechanisms. We hypothesize the following:

H6a. Participants who receive general information on the functionality and application areas of H_2ESS are more accepting of H_2ESS compared to those who do not receive any information.

H6b. Participants who receive general information and information on possible environmental benefits of H_2ESS are more accepting of H_2ESS compared to those who do not receive any information.

H6c. Participants who receive general information and information on possible participation opportunities in the diffusion process of H_2ESS are more accepting of H_2ESS compared to those who do not receive any information.

H7. Participants who receive general information on the functionality and applications of H_2ESS subjectively rate their knowledge of H_2ESS higher.

H8. (Exploratory): Participants who receive general information on the functionality and applications of H_2ESS are more accepting of H_2ESS in residential areas because they subjectively rate their knowledge of H_2ESS higher.

2. Methods

2.1. Participants

1004 participants from Germany participated in this study. They were aged between 18 and 88 years ($M = 52.03$ years, $SD = 15.43$). In line with the population projections based on the 2023 census [72], 50.7% identified as female and 49.3% as male. Participants originated from all 16 German federal states, with most from North Rhine-Westphalia ($n = 209$, 20.8%), followed by Bavaria ($n = 155$, 15.4%), and the smallest share from Bremen ($n = 5$, 0.5%) aligning closely with the data provided by the Federal Statistical Office [73] (Supplementary Figs. 1–2). In terms of the residential environment, 406 participants (40.4%) described their living area as rural, while 580 participants (57.8%) reported living in urban areas. On average, the sample was somewhat more educated than the general German population [74]. Overall, baseline characteristics appeared balanced across experimental conditions. Two variables showed nominal differences at $p < .05$ (affective component of environmental consciousness: $p = .043$; autonomy satisfaction: $p = .018$), but neither remained statistically significant after correction for multiple testing. See Supplementary Table S1 for a detailed demographic overview of the sample.

2.2. Procedure and design

The study was preregistered (see Data Availability statement). Minor deviations from the preregistration concerned terminology, hypothesis ordering, and analytical implementation and are summarized in Supplementary Table S2. These changes were introduced to improve clarity and consistency and did not affect the theoretical content, hypothesized relationships, or interpretation of the study.

Data were collected between April 23 and April 30, 2024, via the panel provider Dynata [75]. Participants were informed about the study procedure, including their right to withdraw at any time, and gave informed consent. They first provided socio-demographic details (Fig. 2). Participants then indicated their voting intention regarding H_2ESS hypothetically installed within a 100-m radius of their residence (see Table 1), objective knowledge of hydrogen, subjective knowledge of H_2ESS, environmental consciousness, perceived autonomy, and perceived social relatedness (see Table 1).

They were randomly assigned to one of four conditions (Table 2) using the survey software's built-in randomization function. In three experimental conditions, participants received a standardized description of the functionality and potential applications of H_2ESS, explicitly defined as the storage of electricity in the form of hydrogen for later energy use. In the general information condition, only this description was provided. In the environmental benefit condition, participants received the general information and additional information on storing surplus renewable energy, increasing long-term energy availability, and supporting the integration of renewable energy into the energy system. In the participation opportunities condition, the general description was supplemented with information on opportunities for citizen involvement in the diffusion process of H_2ESS (full texts are available in the Supplementary Materials, T1–3). In the baseline condition, participants received no information. This condition was included to reflect the current status quo, in which individuals often form opinions about hydrogen technologies without receiving structured information beforehand.

Participants then reported their acceptability of H_2ESS and subsequently reassessed their voting intention and subjective knowledge about H_2ESS. Unless stated otherwise, the term subjective knowledge refers to this post-intervention measure in the following sections. Participants could then explain their reasons for supporting or opposing H_2ESS in open-ended responses. Additionally, participants had the option to indicate whether they needed more information to answer the subjective knowledge assessment items on H_2ESS.

2.3. Measures

All items are presented in Table 1. The full survey materials, including the original items and their translations, are available on OSF (see Data Availability statement). We used two acceptability-related measures that capture different aspects of how participants evaluate H_2ESS. First, we measured acceptability using four items on bipolar scales, rated on a 5-point Likert scale. Second, we assessed participants' voting intention regarding H_2ESS both at the beginning and the end of the survey by asking whether they would vote for or against the installation of a hydrogen storage system within 100 m of their residence, using a 7-point Likert scale [23]. Based on their voting intentions,

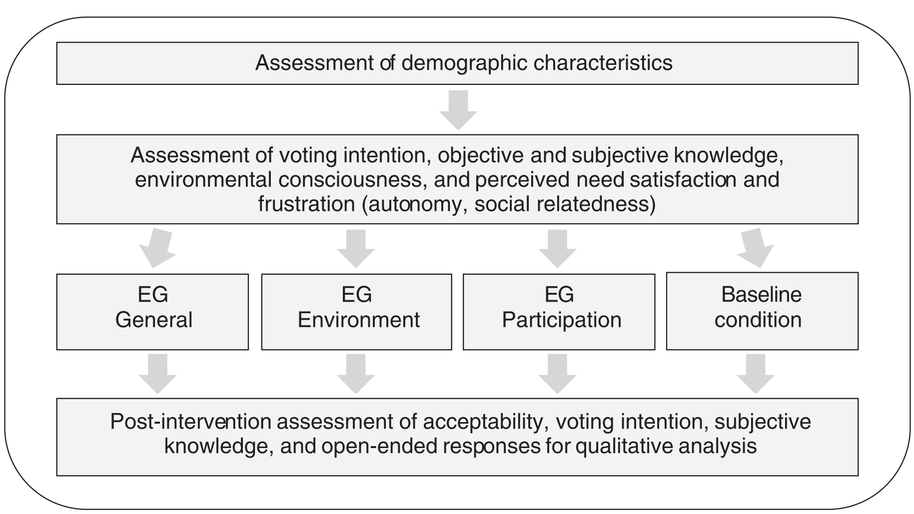

Fig. 2. Research design. EG General = experimental condition with general information, EG Environment = experimental condition with general information and additional information on the environmental benefits of H_2ESS, EG Participation = experimental condition with general information and additional information on participation opportunities in the diffusion process of H_2ESS, Baseline condition = condition receiving no information.

Table 1
Variable and item overview.

Variables	Items	Description	Original	
Voting intention regarding H_2ESS	V_01	If you could vote in your neighborhood on the installation of an H_2 tank within a 100-m radius of your residence, would you vote for or against it?		
Acceptability		I find the installation of an H_2 storage system in my residential area	Huijts & van Wee, $\alpha = 0.93$ [19]	5-point Likert scale
	AC_01	(a) a very bad - a very good idea		
	AC_02	(b) a strong deterioration - a strong progression		
	AC_03	(c) useless - very useful		
	AC_04	(d) not at all important - very important		
Objective knowledge	OK_01	Is H_2 lighter or heavier than air? [Lighter]	Ono & Tsunemi [76]	Dichotomous (yes/no) format
	OK_02	Does H_2 smell? [No]		
	OK_03	Is H_2 flammable in air? [Yes]		
	OK_04	Can H_2 be stored as liquid? [Yes]		
	OK_05	Can H_2 be stored as gas? [Yes]		
Subjective knowledge	SK_01	I know pretty much about H_2 energy storage systems.	Flynn & Goldsmith, $\alpha = 0.93$ [77]	7-point Likert scale (1 = strongly disagree, 7 = strongly agree)
	SK_02[a]	I do not feel very well informed about H_2 energy storage systems.		
	SK_03	Among my circle of friends, I'm one of the "experts" on H_2 storage systems.		
	SK_04[a]	Compared to most other people, I know less about H_2 storage systems.		
	SK_05[a]	When it comes to H_2 storage systems, I really don't know much.		
Environmental consciousness (affective component)[b]	ENV_01	I appreciate initiatives that experiment with sustainable ways of living (e.g., eco-villages, Slow Food movement).	Geiger & Holzhauer, $\alpha = 0.71$ [37]	5-point Likert scale (1 = strongly disagree, 5 = strongly agree)
	ENV_02	I get angry when I see Germany fail to meet its climate protection goals.		
	ENV_03	More environmental protection also means a higher quality of life and better health for everyone.		
	ENV_04[a]	There are natural limits to growth, which our industrialized world has already reached.		
	ENV_05	Each of us is responsible for ensuring that we leave a livable environment for future generations.		
	ENV_06	We need to find ways to live well without depending on economic growth.		
Environmental consciousness[b] (behavioral component)	ENV_07	I buy food from certified organic farms.		5-point Likert scale (1 = never, 5 = always)
	ENV_08	When shopping, I choose products with environmental labels (e.g., Blue Angel, EU Organic Seal, or EU Ecolabel).		
	ENV_09	For my everyday routes, I use a bicycle, public transportation, or walk.		
Autonomy satisfaction (+)	AUT_01	I was free to do things my own way.	Neubauer & Voss, $\alpha = 0.79$ [78]	7-point Likert scale (1 = strongly disagree, 7 = strongly agree)
	AUT_03	My choices expressed my "true self".		
	AUT_05	I was really doing what interests me.		
Autonomy frustration (−)	AUT_02	I had a lot of pressure I could do without.		
	AUT_04	There were a lot of people telling me what to do.		
	AUT_06	I had to do things against my will.		
Social relatedness satisfaction (+)	REL_01	I felt a sense of contact with people who care for me and whom I care for.	Neubauer & Voss, $\alpha = 0.77$ [78]	
	REL_03	I felt close and connected with other people who are important to me.		
	REL_05	I felt a strong sense of intimacy with the people I spent time with.		
Social relatedness frustration (−)	REL_02	I was lonely.		
	REL_04	I felt unappreciated by one or more important people.		
	REL_06	I had disagreements or conflicts with people I usually get along with.		

[a] Item was excluded from analysis due to low factor loadings and cummunalities (see section 3.2).
[b] For exploratory analysis, environmental consciousness was mean-centered to facilitate interpretation and reduce multicollinearity [80].

Table 2
Condition-wise means and standard deviations of acceptability.

Condition	*N*	Mean (Acceptability)	*SD*
EG General	250	9.60	3.88
EG Environment	252	10.34	3.76
EG Participation	252	10.91	4.16
Baseline condition	250	8.72	3.90
Total	1004	9.90	4.01

Note. Acceptability scores range from 0 to 16, with higher values indicating greater acceptability.

we classified participants into three groups: supporters ("I would somewhat vote for it," "I would vote for it," or "I would definitely vote for it"), opponents ("I would definitely vote against it," "I would vote against it," or "I would somewhat vote against it"), and neutral voters ("I would abstain").

Objective knowledge about hydrogen was measured using an adapted version of Ono and Tsunemi's scale [76], translated into German. Four of the original nine items were excluded due to ambiguous wording and potential variability in interpretation, according to consultation with a hydrogen fuel cell expert. This included, for example, the item "Can hydrogen be stored as an immersed form by others?". Participants selected the correct answers from a dichotomous (yes/no) format. To assess subjective knowledge of H_2ESS, we used a German translation of Flynn and Goldsmith's subjective knowledge scale [77]. The translated version was adapted to the specific context of H_2ESS. Subjective knowledge was measured on a 7-point Likert scale. Environmental consciousness was measured using a validated short version of the Environmental Consciousness Scale by Geiger and Holzhauer [37]. We distinguished between affective and behavioral dimensions of environmental consciousness and included both separately in the analyses. Participants rated their environmental consciousness on a 5-point Likert scale. Satisfaction of the psychological needs for autonomy and social relatedness was assessed using the respective subscales of the German Balanced Measure of Psychological Needs Scale [78]. Based on the validated German adaptation of the original English version [79], participants rated their experiences over the past week on a 7-point Likert scale. Consistent with Self-Determination Theory [42], we treated need satisfaction and need frustration as distinct constructs and included both separately in the analysis.

2.4. Statistical analysis

All analyses were conducted using R (version 4.2.2 [81]). Prior to analysis, speeders were excluded. Based on a soft launch (n = 100), a speeder threshold was defined as one-third of the median completion time; participants completing the survey in under 96 s were removed [82]. Missing data among the remaining respondents were then handled using multivariate imputation by chained equations [83]. Data collection continued until the final sample size of $N = 1004$ was reached.

To test the hypotheses, a structural equation model (SEM) was specified. Acceptability was specified as the endogenous latent variable. Predictors included objective knowledge, subjective knowledge, environmental consciousness (affective and behavioral), autonomy and social relatedness (satisfaction and frustration), as well as experimental conditions. Subjective knowledge was additionally included as a mediator of intervention effects on acceptability. Post-intervention subjective knowledge was regressed on pre-intervention subjective knowledge to control for baseline differences and capture intervention-related change. Estimation was conducted using robust maximum likelihood estimation to address non-normality [80], following a two-step procedure with an initial confirmatory factor analysis [84]. Model fit was evaluated using the Comparative Fit Index (CFI), Tucker–Lewis Index (TLI), Root Mean Square Error of Approximation (RMSEA), and Standardized Root Mean Square Residual (SRMR), along with the χ^2/df ratio, based on robust estimators (see Table 3) [61]. Standardized effect sizes were interpreted according to Gignac and Szodorai [85].

We complemented the SEM analysis with exploratory analyses to assess the robustness and heterogeneity of the findings. First, we examined whether environmental consciousness moderated the effect of environmental benefits information on acceptability using a linear regression model with an interaction term. We tested this, because environmental consciousness reflects a value-based orientation and may therefore influence how individuals respond to environmental information [86,87]. Second, we examined whether intervention effects generalized to voting intention as a broader, single-item behavioral outcome for acceptability (Table S3). In addition, exploratory subgroup analyses (for supporters, opponents, and neutral voters) were conducted to assess whether intervention effects on acceptability differed depending on participants' initial voting intention. Results are reported in the Supplementary Materials (Table S4).

Construct reliability was evaluated using Cronbach's α and composite reliability. Convergent validity was assessed via factor loadings and the average variance extracted (AVE). Discriminant validity was confirmed by comparing the square root of AVE with inter-construct correlations and the maximum shared variance, following Fornell and Larcker [88] and Hair and colleagues [89] (see Table S5 in the Supplementary Materials). All assumptions were checked, and a significance level of $\alpha = 0.05$ was used for all tests.

To explore participants' spontaneous reasons for supporting or opposing H_2ESS, we analyzed open-ended responses using qualitative content analysis [90,91], based on principles of grounded theory [92]. Responses containing meaningless strings and responses lacking specific reasoning regarding H_2ESS were excluded. Interrater reliability was assessed using Cohen's kappa, with values of $k \geq 0.7$ indicating sufficient agreement between coders [93]. The achieved agreement exceeded this threshold. Conceptually similar statements were grouped into thematic categories (see Fig. 5), and categories with fewer than five mentions were pooled under "other reasons in favor" or "other reasons against".

Table 3
Model fit indices.

Fit indices	χ^2/df	RMSEA	SRMR	CFI	TLI
Target value	≤ 3.0	< 0.08	≤ 0.08	≥ 0.90	≥ 0.90
Model value	1.70	0.03	0.04	0.97	0.96

Note. RMSEA = Robust Root Mean Square Error of Approximation, SRMR = Standardized Root Mean Square Residual, CFI = Robust Comparative Fit Index, TLI = Robust Tucker-Lewis Index, df = degrees of freedom, $df = 547$.

3. Results

3.1. Descriptive statistics

Acceptability levels were moderate ($M = 9.90$, $SD = 4.01$). Table 2 shows the univariate descriptive statistics for acceptability, post-intervention (see Supplementary Table S6 for variable means and correlations of all variables). $N = 421$ (41.9%) participants were categorized as supporters, 302 (30.1%) as opponents, and 281 (28.0%) as neutral voters based on their responses at the first measurement point before the intervention. See Supplementary Figs. 3–6 for mean acceptability by federal state, education, income, and living area. 436 participants (43.4%) reported that they needed more information to answer the subjective knowledge assessment questions on H_2ESS.

3.2. Measurement quality of the constructs

All multi-item constructs were evaluated using exploratory and confirmatory factor analyses to assess their factor structure and measurement quality. Exploratory factor analyses explored psychometric structures, guided by parallel and scree plots [94], using maximum likelihood estimation with oblimin rotation, allowing for correlated factors [84]. Items were retained if they showed factor loadings of $\lambda \geq 0.40$ and communalities of $h^2 \geq 0.30$ [89]. Full factor loadings are reported in Supplementary Table S7.

For objective knowledge, the five items loaded moderately on a single factor ($\lambda = 0.49$–0.61), explaining 30% of the total variance ($\chi^2(5) = 16.21$, $p = .006$; TLI = 0.97; RMSEA = 0.05, 90% CI [0.02, 0.07]). Although parallel analysis suggested a multi-factor solution, this likely reflects the heterogeneous nature of factual knowledge, where knowledge of one aspect does not necessarily imply knowledge of another [95]. Given our a priori conceptualization of general hydrogen-related knowledge as a single factor, we retained a unidimensional solution. To further examine potential heterogeneity, we conducted exploratory item-level analyses in which each knowledge item was entered separately as a single-indicator predictor of acceptability in the SEM.

For subjective knowledge, three items (SK_02, SK_04, SK_05) were excluded due to low factor loadings ($\lambda = 0.02$–0.47) and low communalities ($h^2 = 0.00$–0.22). The remaining items formed a coherent factor capturing perceived knowledge about hydrogen technology in general (see Table 1).

Environmental consciousness was represented by two factors, reflecting affective and behavioral components in line with Geiger and Holzhauer [37]. One item (ENV_04) was excluded due to low factor loading ($\lambda = 0.28$) and low communality ($h^2 = 0.08$).

Regarding psychological needs, autonomy was modeled using two factors (autonomy satisfaction and autonomy frustration). The same two-factor structure was specified for social relatedness, following prior work [78].

Cronbach's α values indicated satisfactory reliability for all variables ($\alpha > 0.70$) [89]. The composite reliability values for the constructs ranged from 0.72 to 0.92, indicating high internal consistency [89], while most AVE values exceeded 0.50, supporting adequate convergent validity [88]. Results further confirmed discriminant validity for most constructs. However, autonomy and social relatedness frustration did not meet the criterion due to high intercorrelations. Nevertheless, retaining these constructs is theoretically justified [43] as they represent interconnected aspects of basic psychological need frustration. Supplementary Table S5 reports validity and reliability information for all retained items. SEM confirmed an excellent model fit.

3.3. Assumption tests and assessment of the measurement model (H1-H8)

Model diagnostics were conducted prior to SEM estimation. The Mardia test [96] indicated deviations from multivariate normality,

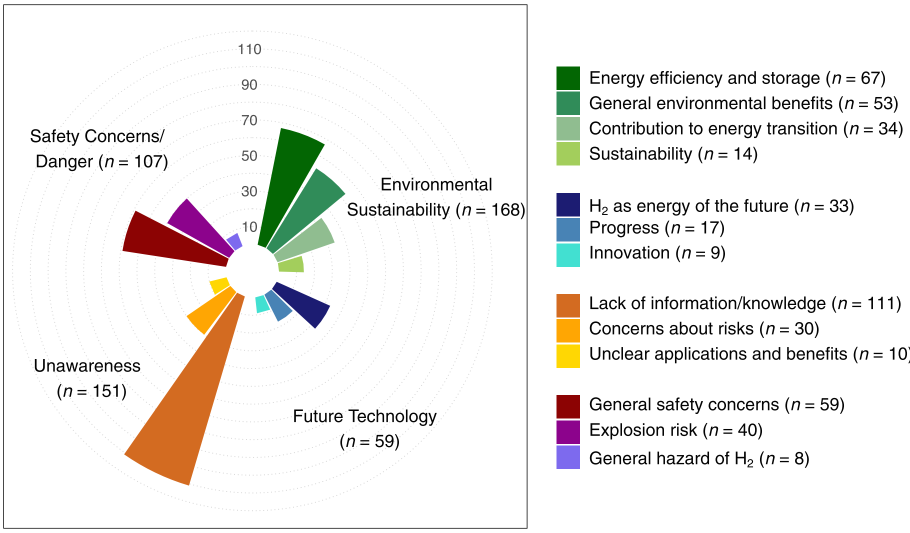

Fig. 5. Visualization of four overarching themes and their associated categories for or against H_2ESS, based on qualitative responses from open-ended questions, reported by $n = 656$ participants. Number of mentions indicated in brackets. The figure displays only those responses that could be assigned to the four higher-order themes; a full overview of all coded categories is provided in Supplementary Table S10.

which were expected given the ordinal Likert-type items [97]. We thus applied robust maximum likelihood estimation [84]. Latent correlations among predictors remained below the 0.90 threshold, indicating no evidence of problematic multicollinearity. Residuals were approximately normally distributed, with minor deviations at the tails. Residuals versus fitted values were centered around zero, with slight indications of heteroscedasticity. Given the use of robust maximum likelihood estimation, analyses are considered robust to these deviations. Following the initial model estimation, modification indices were examined, suggesting additional cross-loadings and the estimation of covariances between items. Only those modifications that could be theoretically justified were implemented to enhance the model.

In the measurement model, we specified residual covariances between Env_05 and Env_06, Env_07 and Env_08, OK_02 and OK_06 as well as between AC_01 and AC_04 due to conceptual overlap (Table 1). The final model showed good fit to the data. While the Chi-square tests were significant for all three models - an outcome often observed with larger sample sizes [84,98] - the relative Chi-square (χ^2/df) was well within acceptable limits, indicating an adequate model fit. Additional fit indices confirmed adequate model fit (Table 3) [98].

As a sensitivity analysis, we re-estimated the SEM after excluding 18 participants who provided clearly meaningless responses in the open-ended question (while retaining missing responses) to examine whether potentially inattentive responding influenced the results. Model fit and substantive results remained largely unchanged, and all conclusions were maintained.

3.4. Socio-psychological predictors (H1-H5)

Participants with better objective knowledge were more accepting of H_2ESS ($\beta = 0.09$, 95% CI [0.01, 0.18], $z = 2.09$, $p = .036$; H1). The association between objective knowledge and acceptability differed across specific knowledge items. Participants who knew that hydrogen can be stored as a liquid ($\beta = 0.12$, 95% CI [0.05, 0.18], $z = 3.50$, $p < .001$), or that hydrogen can be stored as a gas ($\beta = 0.08$, 95% CI [0.02, 0.15], $z = 2.44$, $p = .014$) were more accepting. Links to other knowledge items were non-significant (see Supplementary Table S8 for full modeling results of each knowledge item). Participants were also more accepting of H_2ESS when they subjectively felt more knowledgeable about the technology ($\beta = 0.21$, 95% CI [0.05, 0.38], $z = 2.52$, $p = .012$; H2), and when they reported higher affective environmental consciousness ($\beta = 0.62$, 95% CI [0.12, 1.12], $z = 2.49$, $p = .013$; H3). Acceptability was unrelated to the behavioral component of environmental consciousness ($\beta = -0.31$, 95% CI [−0.86, 0.23], $z = -1.06$, $p = .290$; H3), autonomy satisfaction ($\beta = -0.01$, 95% CI [−0.17, 0.17], $z = -0.05$, $p = .957$), autonomy frustration ($\beta = 0.28$, 95% CI [−0.03, 0.59], $z = 1.76$, $p = .079$), or social relatedness satisfaction ($\beta = 0.07$, 95% CI [−0.08, 0.22], $z = 0.90$, $p = .366$) (H4, H5). However, participants reported higher acceptability when they experienced lower feelings of social disconnection (social relatedness frustration; $\beta = -0.33$, 95% CI [−0.62, −0.04], $z = -2.28$, $p = .023$; H5). Fig. 3 presents the structural model and standardized path coefficients. Supplementary Table S5 reports standardized factor loadings for all indicator items.

3.5. Intervention effects (H6)

All three information types increased acceptability compared to the baseline condition (Fig. 4). Participants who received general information ($\beta = 0.10$, 95% CI [0.03, 0.17], $z = 2.73$, $p = .006$; H6a), environmental benefits information ($\beta = 0.21$, 95% CI [0.14, 0.29], $z = 5.56$, $p < .001$; H6b), or participation opportunities information ($\beta = 0.15$, 95% CI [0.08, 0.22], $z = 4.25$, $p < .001$; H6c) were more accepting of H_2ESS. A complementary one-way ANOVA supported the overall pattern of the results ($F(3,1000) = 14.57$, $p < .001$, $\eta^2 = 0.042$). Post-hoc tests showed the strongest increase for environmental benefits information with participants scoring on average 2.19 points higher than the baseline condition (25.1% increase). Participation opportunities information also increased acceptability (18.6% increase). The effect of general information did not reach statistical significance here (see Supplementary Table S9 for detailed ANOVA results).

3.6. Subjective knowledge (H7, H8)

We tested whether subjective knowledge mediated the effect of the general information condition on acceptability. The higher participants rated their subjective knowledge, the more accepting they were ($\beta = 0.21$, 95% CI [0.05, 0.38], $z = 2.52$, $p = .012$; H2). However, general information had no effect on subjective knowledge ($\beta = 0.02$, 95% CI [−0.02, 0.07], $z = 0.98$, $p = .328$, H7). As a result, the indirect effect via subjective knowledge was not significant ($\beta = 0.01$, 95% CI [−0.01, 0.02], $z = 0.89$, $p = .375$, H8). Accordingly, H7 and H8 were not supported. Table 4 provides an overview of the respective hypotheses and their results.

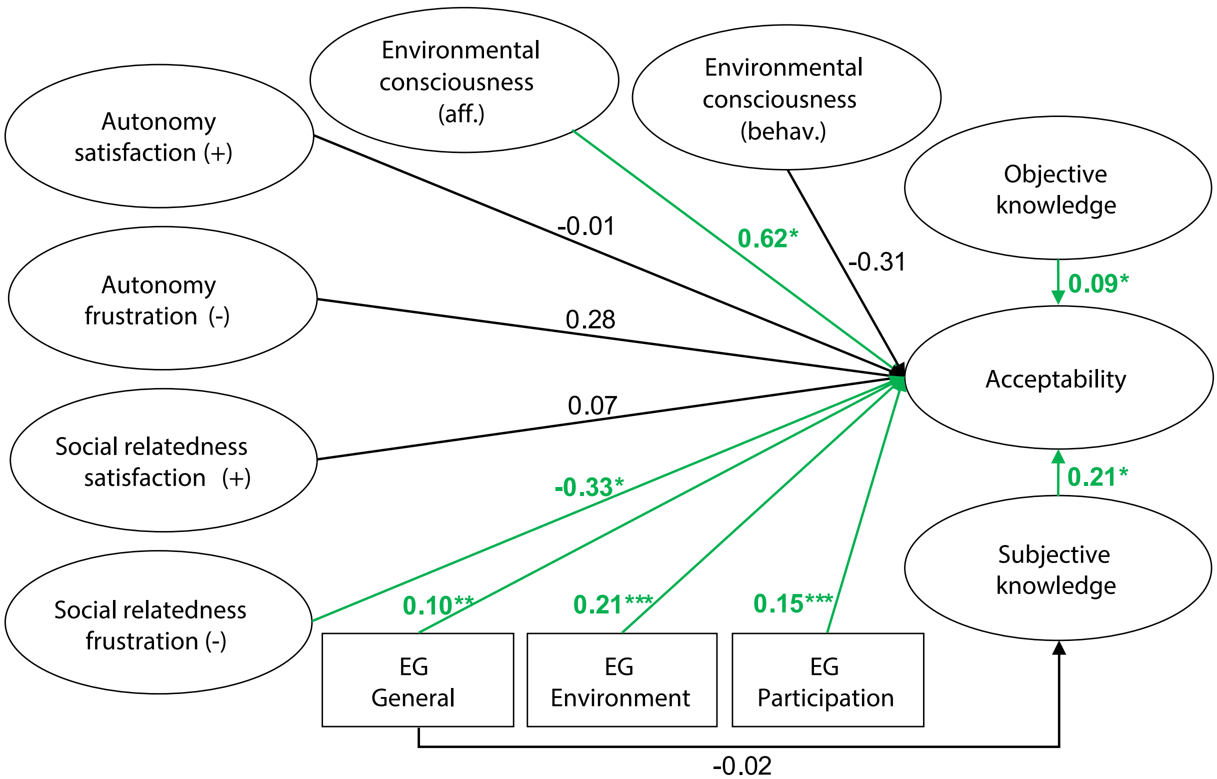

Fig. 3. Structural equation modeling. Green arrows represent significant standardized path coefficients indicating unique prediction contributions. Black arrows indicate non-significant hypothesized effects. $^{*}p < .050$; $^{**}p < .010$, $^{***}p < .001$. For readability, only the mediation pathway via subjective knowledge corresponding to the study hypothesis is visualized; equivalent pathways from the other experimental conditions, which were included in the SEM but not hypothesized, are omitted in the Figure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

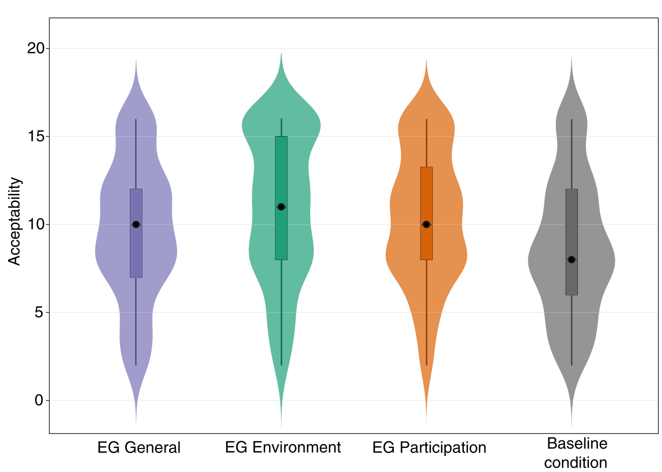

Fig. 4. Distribution of acceptability scores by experimental condition. Each violin shows the kernel density estimation, with an embedded box plot. Acceptability scores range from 2 to 16. Box plots indicate the interquartile range (IQR), with whiskers extending to 1.5 × IQR. Black dots represent the median.

3.7. Exploratory analyses

We tested whether environmental consciousness moderated the effect of environmental benefits information on acceptability using a linear regression model with an interaction term. Although both environmental benefits information and environmental consciousness were positively related to acceptability, their interaction was not significant ($b < 0.001$, $p = .998$). Thus, we found no indication that the effectiveness of communicating environmental benefits differed depending on participants' prior environmental consciousness. However, because the study was not specifically powered to detect interaction effects, these findings should be interpreted as exploratory rather than as conclusive evidence for the absence of moderation. In the Supplementary Materials we report additional analyses examining the intervention effect on voting intentions, as well as subgroup differences (supporters, opponents, neutral voters) regarding acceptability (Tables S3 and S4, Supplementary Fig. 7).

3.8. Exploratory qualitative results

$N = 656$ participants provided valid open-ended responses after excluding 18 meaningless responses and 141 responses lacking specific reasoning. Of these responses, the three most frequently cited reasons supporting H_2ESS were: first, the perceived utility and practical relevance of H_2ESS; second, the potential for efficient energy use and storage; and third, the overall environmental benefits of H_2ESS. Conversely, the three predominant reasons cited against H_2ESS were: first, a lack of information and resultant knowledge deficits; second, general safety concerns; and third, perceived risks associated with explosion hazards. Across all responses, a total of 726 reasons were identified and coded. Many of these reasons could be grouped into four overarching themes. Fig. 5 visualizes these higher-order themes and their associated categories. See Supplementary Table S10 for a comprehensive overview of all categories.

4. Discussion

H_2ESS gains importance for sustainable energy systems [3], and green hydrogen storage systems are vital for the energy transition [9]. Public acceptability is crucial for implementing such new technologies. Acceptability depends on both individual and contextual factors [67].

Table 4
Summary of hypotheses and results.

Hypotheses	Relationships	Std. regression coefficients	*z*-values	*p*-values	Hypotheses results
H1	Objective knowledge → Acceptability	0.09	2.09	.036	+
H2	Subjective knowledge → Acceptability	0.21	2.52	.012	+
H3	Environ. consciousness (aff.) → Acceptability	0.62	2.49	.013	+
	Environ. consciousness (behav.) → Acceptability	−0.31	−1.06	.290	–
H4	Autonomy satisfaction → Acceptability	−0.01	−0.05	.957	–
	Autonomy frustration → Acceptability	0.28	1.76	.079	–
H5	Social relatedness satisfaction → Acceptability	0.07	0.90	.366	–
	Social relatedness frustration → Acceptability	−0.33	−2.28	.023	+
H6a	EG General → Acceptability	0.10	2.73	.006	+
H6b	EG Environment → Acceptability	0.21	5.56	<.001	+
H6c	EG Participation → Acceptability	0.15	4.25	<.001	+
H7	EG General → Subjective knowledge	−0.02	0.98	.328	–
H8	EG General → Acceptability (via Subjective knowledge)	−0.01	0.89	.375	–

Note. – = hypothesis not confirmed, + = hypothesis confirmed.

We thus examined acceptability in two ways. First, we studied links to several socio-psychological predictors. Here, acceptability was higher in those participants who knew more, both objectively and subjectively, and were more environmentally conscious. Participants were not more accepting when they experienced higher need satisfaction but were more accepting when they felt less social disconnection, indicating a negative link of acceptability with need frustration. Second, in a randomized experimental design, participants were more accepting if they received (a) general information about H_2ESS, (b) general information and additional information on positive environmental benefits, or (c) general information and additional information on participation opportunities, compared to a baseline condition receiving no information. Findings for the hypotheses (H1–H8) yield several insights:

First, participants were more accepting when they objectively knew more about hydrogen (H1). Objective, accurate knowledge may facilitate more favorable evaluations of hydrogen technologies, for example by reducing uncertainty or misconceptions and allow for more differentiated evaluations. At the same time, the comparatively small effect size indicates that objective knowledge alone is not the primary driver of acceptability, which is in line with previous studies [25,99]. Further, objective knowledge did not uniformly predict acceptability but varied across items. Specific types of knowledge may thus increase or decrease acceptability. Methodologically, this finding highlights the value of approaches that do not assume homogeneous effects of knowledge in general. Exploratory methods using machine learning techniques such as random forests [100] may help capture non-linear and interaction-based patterns in how specific types of knowledge relate to acceptability.

Second, participants were more accepting when they subjectively knew more about hydrogen (H2). Exploratory subgroup analyses indicated that this was only the case for participants with neutral H_2ESS voting intentions (see Supplementary Fig. 7). This may be because participants with firmly established views are drawing more heavily on prior attitudes or values rather than on their subjective knowledge level [60]. Neutral voters may thus generally be more receptive to new information and more likely to rely on their subjective knowledge. Notably, over 40% of participants also indicated that they lacked sufficient information to confidently assess their level of subjective knowledge (see section 3.1), underscoring the relevance of information quality and accessibility in shaping public responses to H_2ESS.

Third, participants who are more environmentally conscious are more accepting of H_2ESS (H3), confirming other study results [22,31,41,101]. Our study strengthens previous insights by using a validated multi-item measure, thereby improving comparability and measurement quality in a field often characterized by ad hoc measurement instruments [102]. More specifically, only the cognitive-affective component of environmental consciousness was significantly associated with acceptability, whereas the behavioral component was not. This pattern may reflect that acceptability, as an evaluative construct, is more closely aligned with attitudinal orientations, while action-related tendencies are conceptually more distal and often less directly linked to such judgments [103]. Alternatively, support for technological solutions may partly substitute for individual behavioral engagement: Perceiving technological innovation as sufficient to address environmental problems can be associated with lower intentions to behave pro-environmentally [104]. Our exploratory analyses further indicated that participants with higher environmental consciousness were not more or less receptive to information about the environmental benefits of H_2ESS. Although ceiling effects could in principle explain this pattern, they are unlikely, given that acceptability scores still varied sufficiently across all levels of environmental consciousness.

Fourth, participants who reported higher basic need satisfaction (of autonomy or social relatedness) were not more accepting of H_2ESS (H4, H5). One explanation is that need satisfaction was assessed using a generalized, context-independent measure that may not capture domain-specific experiences related to energy-related evaluations, such as feeling autonomous in decisions about hydrogen production and use or feeling socially connected and included in these processes. In line with our hypotheses, however, participants who reported greater frustration of their need for social relatedness in everyday life were less accepting of H_2ESS. This suggests that frustrated social needs may inhibit openness toward the technology. This is consistent with evidence linking social integration and participation to higher acceptability of energy projects [105].

Fifth, participants assigned to the experimental conditions generally showed higher acceptability than participants in the baseline condition, suggesting that information provision itself may play an important role in shaping acceptability of H_2ESS. This interpretation is further supported by the qualitative findings, in which $n = 111$ participants explicitly indicated lacking information or knowledge as a reason for their voting behavior. Conversely, a sensitivity analysis using ANOVA showed that the general information condition did not differ significantly from the baseline condition, although it reached significance in the SEM, where it exhibited the smallest effect. This pattern makes sense, as the general information condition offered the least substantive information, and a SEM is more sensitive to detecting subtle effects. Together, these findings align with evidence that information on hydrogen applications, benefits, risks, and safety measures shapes public evaluations and acceptability by providing the basis for more informed judgments [62,63].

4.1. Implications and conclusion

Our findings have several theoretical implications: First, future research should operationalize need satisfaction within the context of energy technologies by capturing how participants experience autonomy and social relatedness specifically in this domain. Measuring psychological needs with more technology-specific instruments may offer a more accurate understanding of how these needs link to acceptability.

Second, we examined how participants reacted to specific types of information. Future research should examine which types of information individuals actively seek when forming opinions about emerging energy technologies, and how these preferences vary across individuals. Identifying information-seeking patterns may help to design communication strategies that better align with individuals' informational preferences. Individuals do not process information uniformly but tend to engage selectively with information that aligns with their values and prior beliefs about renewable energy technologies [106]. Further, informational interventions that match recipients' values, such as environmental protection, can increase the likelihood that individuals translate them into behavioral intentions [107]. These findings suggest that individuals may seek, prefer and rely on different types of information. This is particularly relevant because insufficient understanding and limited access to information are frequently cited as key drivers of opposition to new energy technologies [20]. At the same time, attitudes toward hydrogen technologies are often generally positive but shift rapidly in response to new information [60]. During early phases of technological diffusion, opinion formation may therefore depend strongly on the information individuals encounter and choose to engage with. For example, making specific information salient, such as carbon labels, can systematically influence choices by increasing attention to climate-relevant attributes [108].

Third, future studies should use mixed-method designs to gain a better understanding of reasons for accepting or opposing hydrogen technology. Qualitative methods, such as interviews, can help identify participants' decision-relevant reasons, while follow-up surveys can assess the generalizability of these reasons [109]. An open-response field such as the one included in our survey can only yield preliminary insights into participants' motivations. Here, a lack of information was the most frequently mentioned reason for opposition, while environmental sustainability was most mentioned as reason for support. Our initial findings underscore the heterogeneity of public responses and suggest the need for more in-depth exploration.

Fourth, there remains a lack of well-established measures of acceptability and its predictors in the context of energy technologies. Advancing scale development is therefore needed for improving measurement precision and comparability across studies. Our study contributes to this effort by adapting and validating an English-language acceptability scale for the German context, using exploratory and confirmatory factor analyses. The resulting scale demonstrated good reliability and construct validity. However, further work is needed to establish their validity across different technologies, contexts, and populations.

We acknowledge the following limitations: Our sample was drawn from a commercial panel, which limits survey inference because the target population may differ systematically from the sampling frame, covering only internet-affine individuals willing to participate in online surveys [110]. Additionally, the information materials were intentionally kept concise and focused on specific aspects of H_2ESS and its implementation, allowing effects to be attributed to specific information types rather than to multifaceted information materials. While this design supports internal validity, it may have limited the extent to which more detailed technical aspects (e.g., physical properties or storage forms) and related risk perceptions were activated. Finally, our selection of socio-psychological predictors did not cover the full range of factors proposed in existing technology acceptability frameworks. Although we included theoretically distinct cognitive, value-based, and motivational predictors, future research should additionally examine other established predictors, such as trust in institutions, which is consistently identified as an important determinant of technology acceptability [20].

Our research has the following practical implications for public communication and participatory planning around H_2ESS: The strong and consistent link between environmental consciousness and acceptability highlights its relevance for public communication. Our findings further provide preliminary evidence that the experience of social disconnection may be linked to lower acceptability of H_2ESS. While these findings should be interpreted cautiously, they suggest that future research may benefit from considering how social experiences relate to technology evaluations. Participatory formats could represent one possible avenue for examining these dynamics in more context-specific ways, as they allow for self-directed, socially engaging involvement [9,111].

Our findings offer an initial indication of the relevance of participation: simply informing participants about participatory opportunities already led to a noticeable increase in acceptability. Public participation itself has been shown to increase acceptability of energy technologies, often via perceived procedural fairness as a central mechanism [112]. Higher levels of decision-making and financial participation have been associated with increased acceptability in German wind energy projects [113], and both experimental and survey evidence shows that opportunities for participation in planning processes can positively affect support for local renewable energy projects [114,115]. Thus, future research should further examine the effects of actual participatory mechanisms on acceptability, such as citizen panels or energy cooperatives, particularly in the context of hydrogen energy [67].

Moreover, information about the environmental benefits of H_2ESS had a strong effect on acceptability that was not significantly moderated by environmental consciousness. Accordingly, communication strategies emphasizing environmental benefits may be relevant for both individuals with higher and lower levels of environmental consciousness, implying that environmental messaging represents a broadly applicable communication strategy.

Finally, while our theoretical framework offers broad applicability, it also reveals a practical tension: Fostering acceptability and participation often requires time- and resource-intensive processes, whereas achieving climate goals depends on the rapid deployment of new technologies. Balancing these competing demands transparently will be essential to maintaining democratic legitimacy while enabling an efficient energy transition. This tension also points to a necessary shift in perspective: rather than treating acceptability as an outcome to be increased for predefined technologies, it may be more useful to focus on designing technologies and implementation processes that can be perceived as acceptable from the outset.

5. Data availability

Individual-level data collected via Dynata cannot be publicly shared due to third-party and consent restrictions. Aggregated results and Supplementary Tables accompany the article. Analysis code (R Markdown files), processed HTML outputs, survey instruments, and experimental stimuli are available at OSF (https://osf.io/3pe96/). The study was preregistered on AsPredicted (https://aspredicted.org/6wsr-rhd4.pdf). See Supplementary Table S2 for minor deviations from preregistration. De-identified datasets can be provided upon reasonable request and institutional approval.

CRediT authorship contribution statement

Rubina Shirin Steller: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Erik Alexander Recklies:** Writing – review & editing, Validation, Investigation, Formal analysis, Data curation. **Petra Schweizer-Ries:** Writing – review & editing. **Astrid Kause:** Writing – review & editing.

Authors' contributions

Rubina Shirin Steller was responsible for the conceptualization of the study. R.S.S. developed the methodology and designed the intervention materials, with support from Erik Alexander Recklies. Both conducted the investigation, with E.A.R. taking a lead role in organizing and implementing the data collection. E.A.R. also led the data curation process. R.S.S. and E.A.R. independently conducted formal analyses, which served as the foundation for further statistical modeling and interpretation carried out by R.S.S. In addition, R.S.S. performed the validation and developed the software scripts. She managed resources, created all visualizations, and was responsible for project administration. R.S.S. wrote the original draft of the manuscript and was responsible for the review and editing. Astrid Kause contributed to writing – review and editing by providing detailed feedback on structure, clarity, and scientific reasoning during the drafting and revision of the manuscript before submission. Petra Schweizer-Ries offered valuable early feedback that supported the refinement of the manuscript's core arguments.

Consent for publication

Not applicable.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author used ChatGPT to improve readability. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2026.104907.

Data availability

Analysis code (R Markdown files), processed HTML outputs, survey instruments, and experimental stimuli are available at OSF (https://osf.io/3pe96/).

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Glossary

H_2ESS: Hydrogen electricity storage systems; local-scale energy storage systems converting surplus renewable energy into hydrogen and back into electricity.