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Public acceptance of hydrogen technologies and hydrogen refuelling stations in Spain

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ABSTRACT

Green hydrogen plays a fundamental role in the transition of energy systems to a low-carbon future. In Spain's climate and energy strategy, hydrogen is considered an essential part of the solution to the challenges posed by the climate crisis. Public acceptance can become a limiting factor for effective implementation of this technology. This study analyses the influence of several psychosocial variables on the acceptance of hydrogen technologies and hydrogen fuelling stations in Spain. A representative sample of 1000 participants from the population living in Spain completed an online survey. Multivariate linear regressions for general (G) and local (L) acceptance show that trust in hydrogen ($\beta_G = 0.52$, $\beta_L = 0.11$), benefits perception ($\beta_G = 0.23$, $\beta_L = 0.15$), subjective knowledge ($\beta_G = -0.05$, $\beta_L = 0.12$) and positive ($\beta_G = 0.11$, $\beta_L = 0.36$) and negative ($\beta_G = -0.06$, $\beta_L = -0.12$) affect are significant predictors in both types of acceptance, but environmental attitudes ($\beta_G = 0.13$), objective knowledge ($\beta_G = 0.04$) and age ($\beta_G = 0.06$) are only significant when considering general acceptance. Moreover, local acceptance is slightly lower than general acceptance, highlighting the need for effective communication and participation in the successful deployment of hydrogen installations.

1. Introduction

Climate change represents the greatest environmental problem affecting the world's ecosystems, demanding coordinated solutions that assist countries in moving towards a low-carbon economy. The Paris Agreement represented the beginning of a shift towards a zero-emission world [1]. Green hydrogen is an energy source that has increasingly been mooted as a possible substitute for fossil fuels, due to its higher energy content and lower environmental impact. It has advantages as an energy source for the future since, in addition to being clean, it can be readily stored and transported [2]. Hydrogen-associated technologies will be crucial for emission reduction in sectors such as industry, transportation, aviation, shipping, chemical and electricity [3]. Consequently, many countries are developing strategies for expanding their hydrogen capacity as a new industry that would contribute to reducing emissions and energy consumption [4–7].

The Renewable Hydrogen Roadmap of the Spanish Government (2020) presents long-term targets for 2030 and 2050, establishing ambitious objectives for 2030, when it foresees an installed electrolyser capacity of 4 GW, and setting a series of milestones in the industrial, mobility and electrical sectors [8]. Although Spain is becoming a major producer of green hydrogen by taking advantage of its abundant renewable energy resources, it is still in the initial phases of large-scale industrial adoption [9]. However, notwithstanding the importance of investments in the development of hydrogen technology at the state and industry level, it is also relevant to consider other aspects such as viability, policies and regulations, and social acceptance [10].

In this context, social acceptance plays a fundamental role in the development of hydrogen energy technologies (HETs) and can even become a limiting factor in its implementation [11]. Scovell [12] found, based on a systematic review of the scientific literature, that few studies have considered the acceptability of HETs beyond specific applications. Likewise, the importance of conducting explanatory studies to identify

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Abbreviations

HET – Hydrogen Energy Technologies
HRS – Hydrogen Refuelling Station
PCA – Principal Component Analysis

the main predictors of social acceptability of HET was emphasised. Weaknesses were found in the use of single-item scales to evaluate psychological constructs, in multiple-item scales with limited psychometric information, and in factor analysis studies that lacked concrete results. Emodi et al. [13] also highlighted the need for studies on societal perception of hydrogen and its applications, as a foundation for hydrogen governance, regulation and policies.

Despite Spain's current national strategic plan for the deployment of hydrogen technology in its strategy for decarbonization and energy transition, and the importance of considering the social dimension in the successful implementation of any energy technology, very few studies on social acceptance of hydrogen technologies have been conducted in Spain. For example, a recent review of green hydrogen from the perspective of social sciences [14] reported that Germany and the United Kingdom lead the way in social acceptance studies, while no studies from Spain were reported. The present study contributes to filling the existing research gaps by: a) providing current information on the analysis of the main factors that play a key role in the social acceptance of hydrogen in Spain, based on predictive and explanatory models; b) expanding the scope of the HET acceptance study, as well as analysing hydrogen refuelling stations (HRS) as a specific application, considering mobility as a strategic line of development in Spain, and c) building on previous studies by providing the results of a PCA as an indicator of the validity and reliability of the employed psychosocial constructs.

The results of this study could guide stakeholders in decision-making, both in the implementation of technology and in the engagement of communities where related projects could be developed.

The following section presents a review of the literature, including the main predictors of social acceptance of HETs studied so far, as well as a review of previous studies conducted in Spain with respect to attitudes towards hydrogen.

2. Literature review

2.1. Identified influencing factors of social acceptance of HET

According to Kovač et al. [5], the success of hydrogen technology for energy transition will depend both on its technical parameters (efficiency and cost of production) and, crucially, on its acceptance by end-users (who know little or nothing about it). For HET worldwide, several predictors of social acceptance of hydrogen technologies have been studied. In attempting to explain social acceptance of HET, these studies have highlighted the relevance of perceived or expected effects. Huijts et al. [15] demonstrated that higher perceived safety risks are associated with a more negative overall evaluation, while higher perceived environmental benefits are associated with a more positive overall evaluation. Itaoka, Saito, and Sasaki [16] also found that acceptance of the placement of an HRS near a respondent's house was negatively influenced by risk perception regarding hydrogen and fuel cell technologies, and positively influenced by recognition of the need for hydrogen infrastructure. Perceived environmental benefits of HET are also a particularly strong positive driver of social acceptance [12].

A recent review of the literature by Steller et al. [17] found that environmental attitude is the most widely studied socio-psychological factor influencing HET acceptance. People with environmentally friendly attitudes are more likely to support hydrogen solutions [18]. Environmental concerns have a strong influence on the acceptance of HRS, especially if the hydrogen comes from renewable energy sources. By contrast, when hydrogen comes from other sources such as natural gas, social acceptance decreases among people who prioritise environmental issues [19,20].

Social trust ranks as the second most researched factor influencing HET acceptance [17]. Some studies evidence the importance of trust in science and technology [13] or institutional trust in the municipality and industry [21–23]. Recently, Häußermann et al. [24] found that acceptance of green hydrogen relies on trust in science, government, the media, and institutions. Another strong determinant of the acceptance of refuelling facilities is whether respondents have confidence in the safety regulations [16]. In Germany, a recent study using a multiple linear regression model found that trust in safety, trust in project managers, information, risk/benefit perception, experience and gender had a significant positive impact on the acceptance of green hydrogen plants [25].

People's emotional reactions to HET also helps explain their degree of acceptance, and this is closely related to how the effects of the technology are perceived. Citizens' emotions, such as anger, fear, joy, and pride, significantly affect their acceptance of HRS, and while negative emotions can lead to resistance against projects, positive emotions can promote [26]. Further studies along these lines are increasingly needed.

Knowledge of hydrogen technology is another factor that has been investigated. Results obtained by Molin [27] indicate that knowledge about hydrogen is not very high: as a fuel it is perceived more as environmentally friendly and inexhaustible than dangerous, so attitudes are quite positive. Tarigan & Bayer [28] suggest that hydrogen acceptance relates negatively to hydrogen knowledge, with greater support for hydrogen development showing among individuals with less knowledge. Huijts & Van Wee [21], on the other hand, suggested that both objective and subjective (self-reported) knowledge have a positive effect on HET acceptability. A recent study examining public acceptance of hydrogen refuelling facilities in Japan, Spain and Norway found that knowledge of hydrogen has a polarising effect on individual acceptance, with greater support among advocates and greater opposition among detractors [29].

Some socio-demographic variables also seem to have an impact on the social acceptability of hydrogen technologies. According to Scovell [12] and Emodi [13], most studies measured gender, age, and education. Studies tend to report that men, the more highly educated, and younger people show greater support for HET [30–32]. Other studies have found no difference between individuals by level of education or age group [20]. Likewise, income level also seems to have a positive effect on general and local acceptance of hydrogen [19,21].

2.2. Social acceptance of HET in Spain

Within the "Plan for the Recovery, Transformation, and Resilience of the Economy" approved by the Spanish government, green hydrogen is promoted as a form of energy storage. The promotion of this fuel was already included in measure 1.7 of the Spanish National Energy and Climate Plan, submitted to the European Commission in 2019. In this plan, Spain described its climate and energy strategy, in which hydrogen was considered an essential part of the solution to the challenges posed by sustainable transport and energy storage [33].

The "Roadmap for renewable hydrogen and its sectoral integration", approved in October 2020, reflects a solid commitment by the Spanish government to renewable hydrogen, including measures (both regulatory and incentivising) that facilitate the achievement of objectives for 2030. Some of the measures included are: the installation of 4 GW of electrolyser capacity; a minimum renewable hydrogen contribution of 25 % to the total hydrogen consumed in all consumer industries; a fleet of at least 5000–7500 light and heavy-duty hydrogen fuel vehicles; and 150–200 renewable hydrogen fuel cell buses [8].

Spain intends to be one of the most important producers and exporters of hydrogen despite the uncertainty in real hydrogen production and its associated water requirements [34]. Likewise, the acceleration in the approval of renewable hydrogen projects in Spain could compromise public participation, with fast-tracking procedures potentially exacerbating opposition and reducing social acceptability [35]. Additionally, very few relevant social acceptance studies have been conducted at the national level. To date, only a small number of projects have examined Spanish residents' public attitudes towards hydrogen technologies either generally or at the local level.

Irribaren et al. [36] conducted the first identified empirical study aimed at assessing public attitudes in Spain towards the use of hydrogen technology for transport. The results, obtained from a sample of 1005 respondents, showed a high level of awareness of hydrogen as a transport fuel. Likewise, public perception of the potential implementation of hydrogen technologies in the public transport system was significantly favourable. Authors found that respondents were willing to accept hydrogen as a key energy carrier within the energy and transport sector.

European project HYACINTH (Hydrogen acceptance in the transition phase) aimed to achieve a greater understanding of the social acceptance of hydrogen technologies and applications at the European level, in order to facilitate their development and introduction to the market in seven countries, including Spain. The results of this project, by Oltra et al. (2017) [37], found that respondents in the seven countries had a positive initial attitude towards HET. Overall, the results showed higher levels of awareness of hydrogen fuel cell technologies in Germany and Norway, and lower levels in Spain, France and the UK. , even though social acceptance of hydrogen fuel cell electric vehicles was higher in Norway and Spain. Public acceptance of hydrogen fuel cell technology was 72 % in Spain and the main determinants were affect, perceived benefits, preference for alternative technologies, trust, and age.

Although Ellis [38] acknowledges the importance of the dynamic nature of social acceptance and suggests further research to improve our understanding of it, no further studies have been identified in Spain in reference to predictors of social acceptance. In a recent cross-country comparative study by Huan et al. [29], respondents in Spain were in favour of HRS deployment (45.5 %), even more so than in Norway and Japan, where respondents were more reticent. This finding reinforces the need to understand what are the main factors that can influence the high level of social acceptance that currently exists in Spain. Technology acceptance is a complex and multi-faceted phenomenon. General acceptance of a technology may differ from local acceptance [39,40]. Not-In-My-Back-Yard (NIMBY) responses [41] have been used extensively to explain public opposition to energy projects and technologies at the local level [42,43]. Nimbyism occurs when citizens object to or protest against energy projects (e.g., wind farms) being sited in proximity to their property or place of residence, despite these citizens expressing general support for the technology (e.g., wind energy). Local communities might experience more direct impacts, both positive and negative, when technological infrastructure is built in a specific location. Thus, high levels of broader public acceptance do not necessarily translate into high levels of community acceptance at the local level [43,44].

Based on findings from previous studies, the present study aims to empirically analyse the influence of several psychosocial variables on the acceptance of HET and HRS in Spain. This study is part of the international SUSHY project (SUStainability and cost-reduction of Hydrogen stations through risk-based, multidisciplinary approaches) and aims to reinforce current knowledge in relation to the main predictors of general and local acceptance of HET.

3. Method

3.1. Questionnaire

The study was designed with a quantitative methodology through a cross-sectional ad hoc questionnaire. The development of questionnaire items was based on a scientific literature review of previous studies [21,23,30,45,46]. The survey design included a pilot test prior to data collection, which allowed improvements to be made to the final version of the questionnaire. The first part of the survey explained the objective of the study to the participants, as well as the ethical rules for anonymity and confidentiality in the handling of data. The questionnaire comprised three main sections: socio-demographic questions, attitudinal questions, and hydrogen accident awareness. The socio-demographic sections included questions on gender, age, highest education level achieved, and household annual income. In the attitudinal section, questions were grouped according to theoretical constructs, the items within each construct being randomly ordered for each respondent (see Table 1).

Some very general information about hydrogen technology (Fig. 1) and regarding hydrogen fuelling stations (Fig. 2) was provided in the questionnaire:

Please read the information on hydrogen fuel and fuelling stations carefully and answer the following questions.

- Hydrogen is a fuel that, when consumed in a fuel cell, produces only water, thus becoming a promising fuel option for transport and other industry sectors.
- Hydrogen fuelling stations are places to refuel equipment with hydrogen fuel cells, like vehicles, boats, and portable power generation products.

Hydrogen fuelling stations are divided into **onsite** and **offsite** stations, depending on whether they can produce hydrogen.

- **Onsite stations** are equipped with hydrogen production facilities.
- **Offsite stations** rely on logistics to supply externally produced hydrogen.

The two types of hydrogen fuelling stations mentioned above can either be newly built or be placed at an existing petrol station.

As shown in the picture below, the operation of a hydrogen fuelling station consists of four processes, i.e., **production or transportation**, **storage**, and **dispensing** of hydrogen fuel.

Finally, we asked about hydrogen fuelling station accident awareness ("I have heard of hydrogen explosions and fires at a petrol station", yes/no) and petrol station distance ("Do you know the distance to the nearest petrol station to your place of residence?", yes/no). A 5-point

Table 1
Description of the sample (N = 1000).

Variables	Categories	Frequency	Percentage
Gender	Men	500	50.0
	Women	500	50.0
Age	18–28 years	152	15.2
	29–39 years	217	21.7
	40–50 years	271	27.1
	51–60 years	218	21.8
	>60 years	142	14.2
Education level	High school or below	14	1.4
	Senior high school	126	12.6
	Secondary technical school	348	34.8
	Graduated	385	38.5
	Post graduated	119	11.9
	Other	8	0.8
Household annual income	<14.000 €	138	13.8
	14.000–28.000 €	299	29.9
	28.000–42.000 €	301	30.1
	42.000–56.000 €	130	13.0
	56.000–70.000 €	73	7.3
	70.000–84.000 €	29	2.9
	84.000–98.000 €	19	1.9
	>98.000 €	11	1.1

Please read the information on hydrogen fuel and fuelling station carefully and answer the following questions.

- Hydrogen is a fuel that, when consumed in a fuel cell, produces only water, thus becoming a promising fuel option for transport and other industry sectors.

- Hydrogen fuelling stations are places to refuel equipment with hydrogen fuel cells, like vehicles, boats, and portable power generation products.

Fig. 1. First piece of information provided to participants in the questionnaire (between the subjective knowledge and trust questions).

Hydrogen fuelling stations are divided into **onsite** and **offsite** stations, depending on whether they can produce hydrogen.

- **Onsite stations** are equipped with hydrogen production facilities.
- **Offsite stations** rely on logistics to supply externally produced hydrogen

The two types of hydrogen fuelling stations mentioned above can either be newly built or be placed at an existing petrol station.

As shown in the picture below, the operation of a hydrogen fuelling station consists of four processes, i.e., **production or transportation**, **storage**, and **dispensing** of hydrogen fuel.

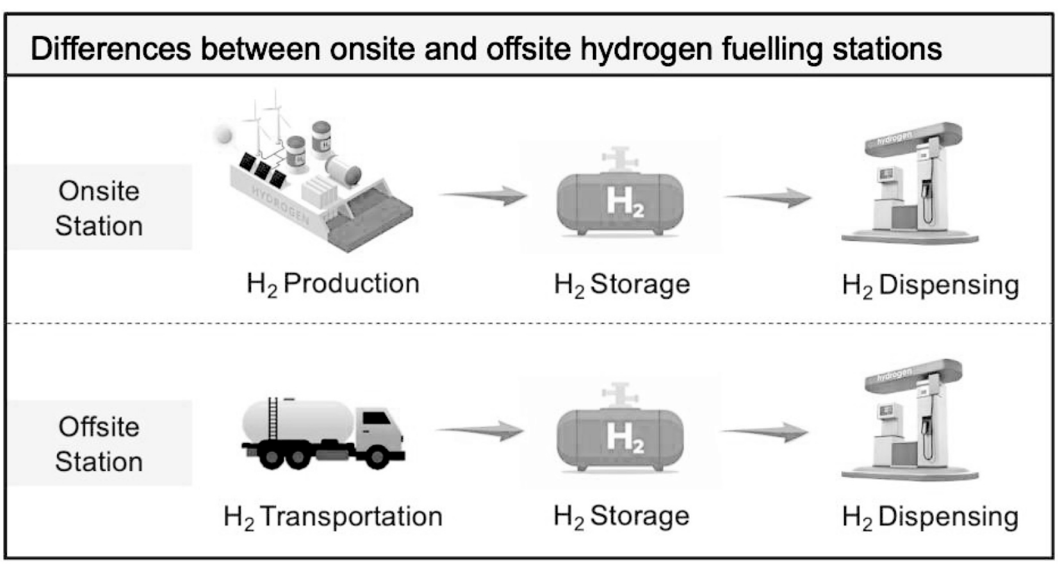

Fig. 2. Second piece of information provided to participants within the questionnaire (after the affect questions).

Likert scale was used for all the items with the exception of objective knowledge, with a true/false scale that also included the "don't know" option. The questionnaire was uploaded into an online version and finally administered between December 2022 and January 2023, by the professional international market research company in charge of recruiting the sample.

3.2. Participants

The sample consisted of 1000 participants living in various regions of Spain, with quotas for both age and gender, to ensure a representative sample of the population in terms of these variables. The sample size of 1000 participants was chosen based on available funding and the availability of panel participants. This sample size is sufficient to accurately estimate the target parameters, as it provides a precision of 0.11 for estimating the mean acceptance of hydrogen with a confidence level of 95 %, an SD = 0.86 (the highest value empirically obtained between general and local acceptance) and an infinite population. The representativeness of the target population was guaranteed by the sampling procedure used.

Therefore, 50 % of men and 50 % of women were proportionally distributed in the different age groups. The average age of the participants was 44.1 (SD = 13.5) years old, in the range 18–69. Regarding education, 49.2 % of the participants were non-university while 50.8 % had a university degree. In relation to income, 43.7 % of the sample earned less than 28,000€, 43.1 % between 28,000 and 56,000€, and 13.2 % more than 56,000€ (Table 2). The participants were distributed among the different provinces of Spain. For example, 12 % of respondents came from Barcelona, 19 % from Madrid, 6 % from Valencia and 5 % from Seville, representing the major cities. Other more rural provinces had a lower participation rate of between 0.3 and 1.5 %.

3.3. Statistical analysis

The statistical analysis was conducted using Stata 18. First, to empirically verify the grouping of items measuring the same construct, two principal component analyses (PCAs) were performed: first, for the set of 40 items defining the constructs that act as input or independent variables, and second, for the set of nine items defining the output or dependent variables. PCA is a widely used statistical procedure in the social sciences that reduces the dimensionality of data by converting a large set of items into a smaller set of components (also called factors or scales) that retain most of the original information, as measured by the

Table 2
Loading matrix for the 8-component solution from principal component analysis with varimax rotation for the 40 input items.

	Factor loadings							
Factor name and loading items	1	2	3	4	5	6	7	8
Environmental consciousness								
People need to live more sustainable lifestyles					0.83			
Our lives need more renewable energy products					0.79			
Concern about climate change and global warming					0.86			
Concerned about the depletion of fossil fuels					0.72			
Trust in H2 technology								
HFCT are reliable enough for industrial and commercial use						0.73		
HFCV in use or available on the market are safe enough						0.75		
The risk of HRS currently in operation is under control						0.79		
There are protective measures against the risks of H2 fuel						0.71		
Perceived benefits								
H2 energy usefulness for achieving carbon neutrality		0.84						
H2 energy usefulness for alleviating global warming		0.83						
H2 energy usefulness for reducing reliance on fossil fuels		0.82						
HRS usefulness for people living nearby		0.71						
HRS usefulness for developing a green local economy		0.83						
HRS usefulness promoting an environment-friendly society		0.82						
Positive affect								
Feelings evoking an HRS in the neighbourhood: Joy							0.83	
… hope							0.82	
… Pride							0.83	
Negative affect								
… Worry				0.80				
… Stress				0.87				
… Fear				0.87				
… Anger				0.79				
Perceived risks								
Likelihood of an accident occurring H2 production	0.77							
Likelihood of an accident occurring H2 transportation	0.77							
Likelihood of an accident occurring H2 storage	0.76							
Likelihood of an accident occurring H2 dispensing	0.74							
Severity of accident in H2 production for nearby residents	0.82							
Severity of accident in H2 transportation for nearby residents	0.84							
Severity of accident in H2 storage for nearby residents	0.86							
Severity of accident in H2 dispensing for nearby residents	0.85							
Objective knowledge								
H2 is lighter than air								0.63
H2 is odorous								0.62
H2 is flammable								0.27
H2 is in a liquid state								0.55
HFC use the chemical energy of H2 to produce electricity								0.64
HFC emit water vapour and carbon dioxide								0.49
HFC products cleanness depend on how H2 is obtained								0.61
Subjective knowledge								
How much do you know about the benefits of H2			0.85					
How much do you think you know about the drawbacks of H2			0.84					
How much do you think you know about FCV			0.89					
How much do you think you know about HRS			0.90					
Eigenvalue	8.14	6.02	3.89	2.34	1.97	1.70	1.48	1.28
% of explained variance	20.4	15.1	9.7	5.8	4.9	4.2	3.7	3.2

H2= Hydrogen, HFCT = hydrogen fuel cells technologies, HFCV= Hydrogen fuel cells vehicles, HRS = hydrogen fuelling stations.

percentage of explained variance [47]. PCA is currently used in various research fields, such as new foods acceptance [48], determination of polygenic risk in mental disorders [49] or exploration of factors shaping attitudes and intentions towards automated buses [50]. Each original item contributes to the definition of a certain component with a quantity called factor loading. Several criteria exist to determine the optimal final number of components. Following standard recommendations, the following four were used: a) the variance explained by the component is greater than that explained by one individual item; b) there is a nonlinear change in the percentage of variance explained by consecutive components; c) the variance explained by the component exceeds that explained by a random component; and d) the ease of interpretation of the components. Regarding the last criterion, two transformations of the components, called varimax and oblimin rotations, were applied to facilitate interpretation of the components. Varimax rotation generates independent components, while oblimin rotation allows the new components to be related. Once the number of selected components was determined, the goodness of fit for the selected solution was assessed, and the variables representing each new component were generated as the mean of the items that defined it. For example, as detailed in the next chapter, applying PCA to the responses to the 40 questions about attitudinal aspects related to hydrogen acceptance suggested grouping them into eight new components, such as Environmental Consciousness, Perceived Benefits, etc. Furthermore, applying PCA to the responses to the nine questions about hydrogen acceptance confirmed two types of acceptance, namely general and local acceptance.

Once the eight attitudinal and two acceptance components were generated, two multivariate linear regressions were estimated, using the eight attitudinal components along with demographic measures (gender, age, education level, and income) as independent variables. One regression considered the general acceptance of HET as the dependent variable, while the other focused on the local acceptance of HFS. Accident awareness, petrol station distance, and general hydrogen acceptance were included as adjustment terms in the analysis of local HFS acceptance to eliminate their potential influence on the studied association.

4. Results

4.1. Principal component analysis

The PCA with the 40 input items was firstly executed. The analysis started with the standardization of the 40 items:

$$Z = \frac{X - \mu}{\sigma}$$

Were X is the data matrix with 1000 rows being the participants and 40 columns being the input items, μ is the mean of each item and σ is its standard deviation. Next, the variance - covariance matrix between standardized items is generated:

$$C = \frac{1}{n-1} Z^T Z$$

Where n is the sample size (1000 participants) and Z^T is the transposed variance – covariance matrix. Using Spectral theory the eigenvectors (components of maximum variance) and eigenvalues (variance of the eigenvector) of the C matrix are derived, together with the loading matrix containing the coefficients to apply to each of the 40 input items to generate the new components. Loading coefficients, also called factor or component loadings, greater than 0.30 are considered high. This is a complex mathematical process that interested readers can find explained in Kuttler (2025) [51]. Eigenvalues are them sorted in descending value and different criteria (in our study the four criteria indicated in statistical analysis) are applied to decide the optimum number of selected components. Finally, the original data matrix could be projected onto the k selected components to generate the reduced data matrix:

$$X_{reduced} = Z\,\lambda_k$$

Where λ_k is the loading matrix for the k selected components. Nevertheless, it is usual that each new component of the reduced data matrix is generated averaging the original items with loadings factor greater than 0.30 in those components. To facilitate interpretation of the selected components different rotation of the selected components have been proposed [52]. Varimax and oblimin rotation were applied to our results. Varimax rotation suggested an eight-component solution that retained 67 % of the total initial variance. Oblimin rotation did not improve the interpretation of the selected components. Moreover, the mean correlation between the eight components was low (0.16), so oblimin rotation was discarded and a varimax solution chosen. Goodness of fit of the selected PCA solution was assessed through residuals analysis. The residual is defined as the difference of the original correlation between each pair of items minus the reproduced correlation from the selected components, and values lower than 0.05 are considered adequate.With our data, out of a total of 40 × 39/2 = 780 residuals, a 90.4 % were lower than 0.05 and their mean was 0.02 (SD = 0.03).

As shown in Table 2, this solution yielded a structure in which all the items of risk perception loaded in the first factor (thus, not separating risk severity from risk likelihood) while all the items measuring benefits for society and the environment loaded in the second factor. All the other scales stand alone: subjective knowledge in the third factor, negative affect in the fourth, environmental consciousness in the fifth, trust in the technology in the sixth, positive affect in the seventh, and objective knowledge in the eighth. Objective knowledge was the factor with the lowest factor loadings, especially for Item 3 (less than 0.30).

The best solution found in the second PCA with varimax rotation for the nine output items (dependent variables) established two components that explained 74.44 % of the variance (see Table 3). Oblimin rotation was selected as it improves the interpretation of the data, and because the correlation between the two components was medium (0.48). For residuals, 63.9 % were lower than 0.05 with a mean of 0.04 (SD = 0.04).

4.2. Reliability: internal consistency

As a measure of internal consistency of the items measuring the same construct, Cronbach's alpha was calculated for the set of items defining each component (Table 4). The original publication established that alpha values greater than 0.80 indicated good internal consistency [53].

Table 3
Loading matrix for the 2-component solution principal from principal component analysis with oblimin rotation for the 9 output items.

	Factor loadings	
Factor name and loading items	1	2
General H2 acceptance		
I am optimistic that hydrogen technologies will lead us to a sustainable society	0.86	
Hydrogen technologies provide a solution to environmental problems	0.90	
I Support the development and applications of hydrogen technologies	0.86	
Hydrogen is a promising green fuel for the future	0.85	
Creating a hydrogen society is a sensible strategy	0.85	
Local H2 acceptance		
Agreement with HRS in the neighbourhood: A newly built onsite HFS		0.85
Agreement with HRS in the neighbourhood: A newly built offsite HFS		0.83
Agreement with HRS in the neighbourhood: An existing petrol station-based onsite station		0.88
Agreement with HRS in the neighbourhood: An existing petrol station-based offsite station		0.86
Eigenvalue	5.01	1.69
% of explained variance	49.5	42.4

Table 4
Cronbach's alpha and descriptives (mean, standard deviation and median) of the independent and dependent variables.

Independent variables	# of items	Alpha	M	SD	Md
Environmental consciousness	4	0.861	4.02	0.91	4.25
Trust in H2 technology	4	0.866	3.56	0.84	3.50
Perceived benefits	6	0.921	3.95	0.84	4.00
Positive affect	3	0.879	3.50	1.09	3.67
Negative affect	4	0.902	2.14	1.07	2.00
Perceived risks	8	0.925	2.75	0.81	2.88
Objective knowledge	7	–	0.50	0.27	0.57
Subjective knowledge	4	0.922	2.34	1.08	2.00
Dependent variables					
General H2 acceptance	5	0.917	3.87	0.83	4.00
Local H2 acceptance	4	0.878	3.42	0.86	3.50

Note: All variables had values range 1–5 except objective knowledge that had 0-1 values range.

This criterion has endured over time and continues to be applied in recent research [54–56]. Cronbach's alpha for the objective knowledge component was not calculated because it is a performance test scale, with answers that can be assessed as correct or incorrect. Therefore, it does not make sense to expect similar responses for all the items forming this component. For the remaining components, all alpha values were higher than 0.80, which indicates that all the scales reached a very satisfactory degree of internal consistency.

4.3. Descriptive analysis

Measured objectively and subjectively, respondents had a medium-low level of knowledge about hydrogen (Table 4). Participants exhibited high environmental consciousness and medium-high trust in hydrogen technology. The benefits from hydrogen were perceived to be higher than the risks. In general, respondents associated more positive emotions (joy, hope, and pride) with hydrogen than negative ones (worry, fear, stress, and anger). Regarding the dependent variables, general acceptance of hydrogen technology was slightly higher than local acceptance of HRS.

The bivariate correlations between input and output measures are presented in Table 5. According to Cohen [57], medium to low correlations were found between general acceptance and some independent variables such as trust ($r = 0.75$), benefits perception ($r = 0.61$), environmental consciousness ($r = 0.49$), and positive affect ($r = 0.46$). Similarly, local acceptance was mainly correlated with positive affect ($r = 0.56$), trust ($r = 0.48$), and benefits perception ($r = 0.43$).

4.4. Multiple linear regression analysis

Fig. 3 shows the results of the linear model, predicting general hydrogen acceptance. The set of predictors achieved a high percentage of explained variance (66.9 %). When considering as relevant every coefficient with a standardised beta weight greater than 0.10 in absolute value and a p-value below 0.05, four predictors were found. "Trust in H2 technologies" emerged as the strongest predictor, followed by "Perceived benefits", "Environmental consciousness", and "Positive affect", all of them having a direct effect on general acceptance. Other determinants with low but statistically significant effect were found, with "Negative affect" and "Subjective knowledge" showing an inverse relationship, and "Objective knowledge" having a direct effect. Regarding the socio-demographic variables, only age stands out as statistically significant with a direct relationship to general acceptance.

Fig. 4 shows the results of the linear model, predicting local H2 acceptance. Hydrogen fuelling station accident awareness ("I have heard of hydrogen explosions and fires at a petrol station"), petrol station distance ("Do you know the distance to the nearest petrol station to your place of residence?"), and general H2 acceptance were included as adjustment variables in the regression model for local hydrogen acceptance. Very few participants had heard about hydrogen accidents in petrol stations (9.8 %). Approximately 40 % of the sample lived in a range of between 300 and 1000 m from a petrol station. Twenty-three percent of the sample lived further away, while only 8 % lived within 50 m of a petrol station. The model explained a satisfactory 41.9 % of the variance in local acceptance of HRS. Five predictors with a standardised beta weight greater than 0.10 in absolute value and a p-value below 0.05 were found. "Positive affect" emerged as the strongest predictor, followed by "Perceived benefits, "Trust", "Negative affect", and "Subjective knowledge". Neither other determinants nor socio-demographic variables were statistically significant.

5. Discussion

5.1. Overall findings

First, our results confirmed a generally positive perception of hydrogen technologies. A low level of risk perception was found, with perceived benefits higher than risks. Trust in the technology also obtained a moderately high score. Moreover, respondents associated more positive emotions (joy, hope, pride) than negative ones (worry, fear, stress, anger) with hydrogen. Taken together, this indicates a favourable attitude towards hydrogen in Spain, which was previously found by Iribarren et al., in 2016 [36], and Oltra et al., in 2017 [37]. Thus, in the last years, during which we have witnessed important advances in hydrogen technology in Spain, the attitude of the public has not changed significantly in relation to previous findings.

Previous studies in other countries have already underlined that hydrogen technologies have mostly been evaluated as neutral to positive, while participants' knowledge of, familiarity and experience with these technologies were rather low [30,40,58]. In comparison to most of the previous studies in Spain [37,59,60] it seems that, despite significant deployment of the technology during the last years, knowledge levels remain low to medium. Only the study by Iribarren [36] reported a high level of awareness of hydrogen as a transportation fuel in Spain. This could be explained by the fact that only a very general question on awareness was used by these authors ("Are you aware of the existence of research activity on hydrogen in the field of energy and transport?" with "yes/no" response options) while in our study, subjective and objective knowledge were measured using several questionnaire items.

In addition, we found that the level of knowledge about hydrogen was lower when measured subjectively than objectively. This would mean that participants think they know less than they really do. In addition, subjective knowledge was predictive of local acceptance of HRS, but objective knowledge did not have a relevant effect. Following the distinction made by House et al. [61], objective knowledge (measured with a knowledge test), and subjective knowledge (self--reported by participants), are moderately correlated but not identical.

Table 5
Zero-order correlation between independent and dependent variables.

	EC	T	BP	PA	NA	RP	OK	SK
GA	0.49*	0.75*	0.61*	0.46*	−0.29*	−0.05	0.14*	0.15*
LA	0.26*	0.48*	0.43*	0.56*	−0.24*	−0.11*	0.13*	0.27*

EC = Environmental consciousness, T = Trust in H2 technology, BP= Benefits perception, PA= Positive affect, NA=Negative affect, RP= Risk perception; OK= Objective knowledge, SK= Subjective knowledge, GA = General acceptance, LA = Local acceptance. *$p < 0.01$.

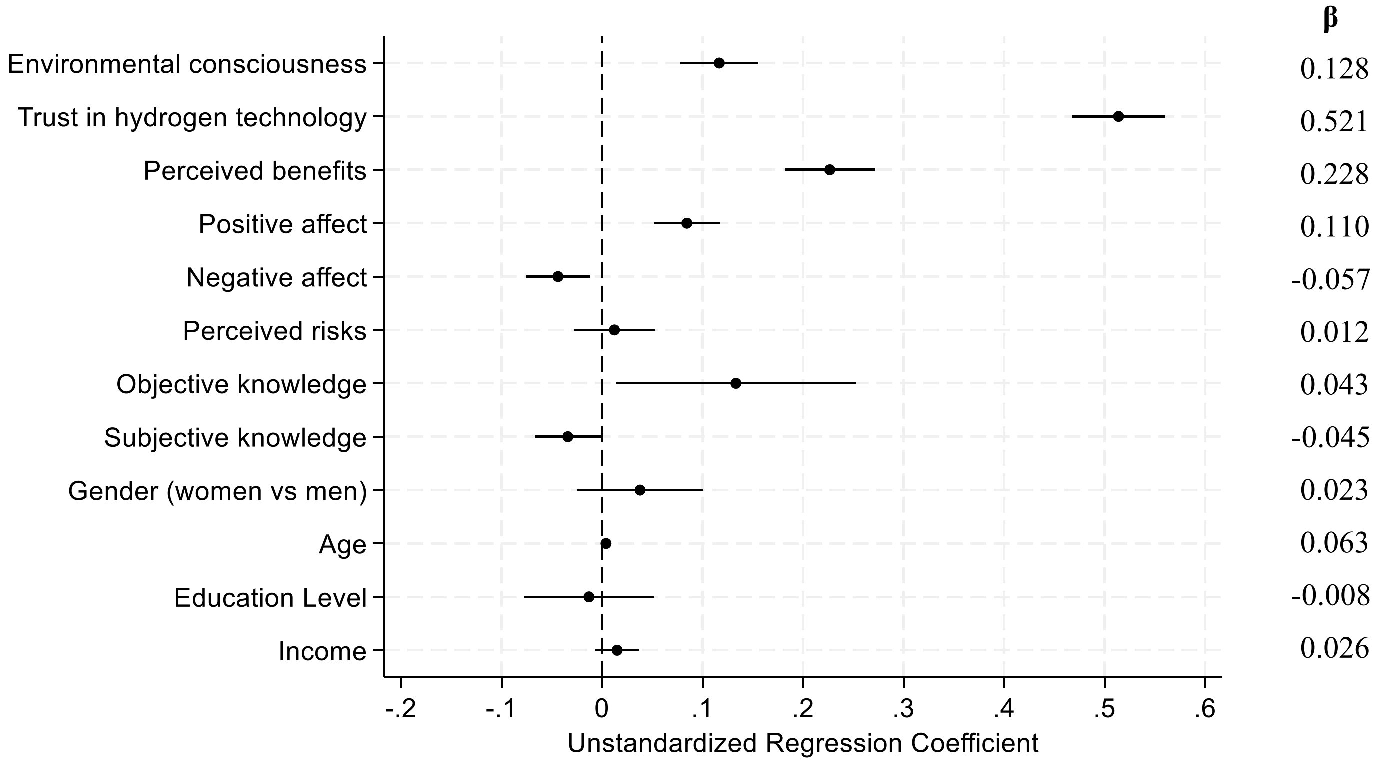

Fig. 3. Linear regression for General acceptance of hydrogen technologies
Adjusted $R^2 = 0.669$; β = Standardised regression coefficient.

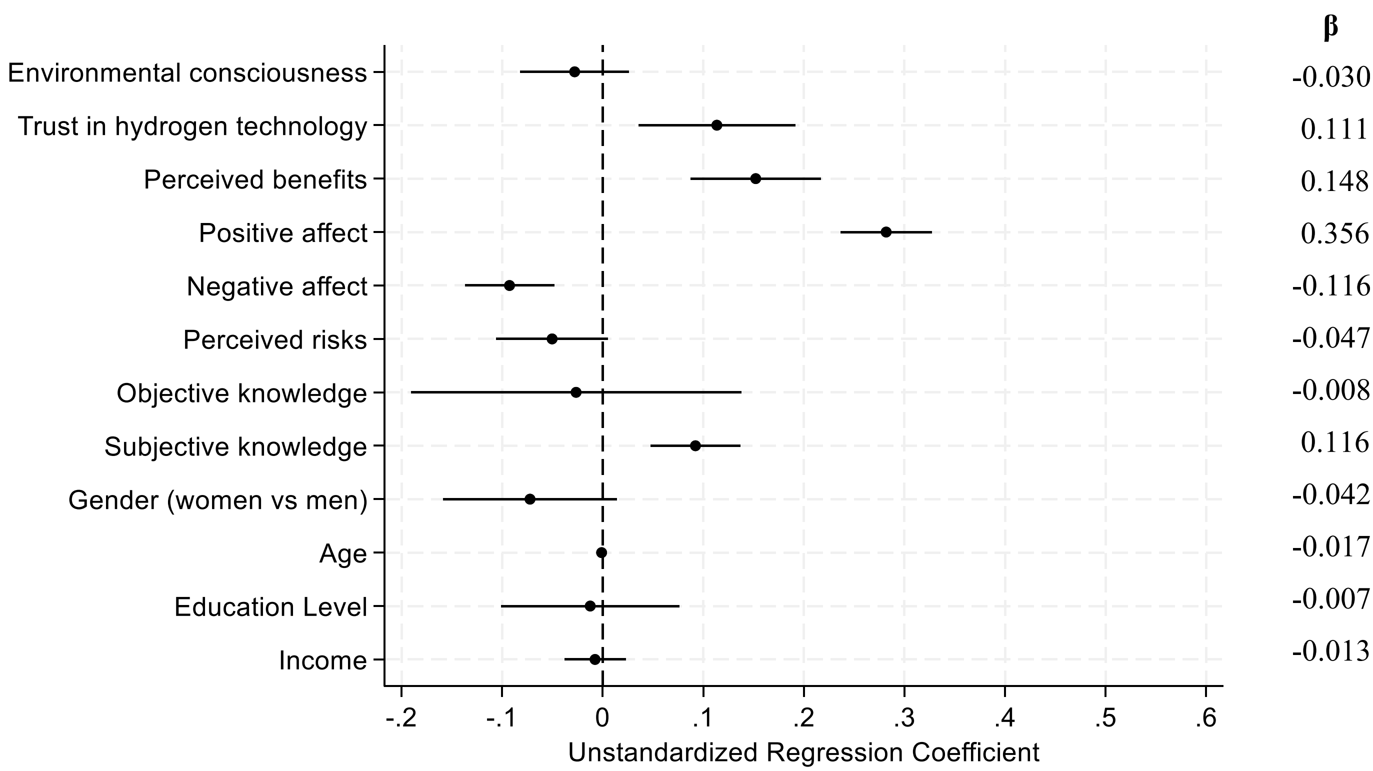

Fig. 4. Linear regression for Local acceptance of hydrogen refuelling stations
Adjusted $R^2 = 0.419$; β = Standardised regression coefficient. Model adjusted by Accident awareness, Petrol station distance and General Hydrogen acceptance.

The study by Yap & McLellan [62] in Japan also showed a gap in public understanding of hydrogen, with actual knowledge being lower than self-reported. Prior knowledge has been shown to act as a driver of hydrogen acceptance [30], especially in the context of transportation [63].

Second, our findings suggest that, as reported in previous studies, general acceptance of the technology and local acceptance of technological application are different [11], and might be explained by different factors. It was found that general acceptance of HET was slightly higher than local acceptance of HRS. Evidence from previous social studies on hydrogen, but also on other sustainable technologies, was along the same lines. For instance, Macht et al. [39] carried out a study in Germany on social acceptance of biorefineries and aquaponics as a key factor for transition towards a sustainable bioeconomy. They found lower local acceptance of both biorefineries and aquaponics when compared to general acceptance rates, pointing to the NIMBY effect: opposition by residents to proposed developments in their local area, despite being in favour of the technological development at a more general level. In the case of HRS, Iribarren et al. [36] found that Spaniards were supportive of the infrastructure, but objected to these facilities being located within residential zones. Similarly, in Germany, Schönauer & Glanz [40] found a highly positive perception of hydrogen on a general level. However, they found that this high level of acceptance decreased for hydrogen infrastructure implementation in the neighbourhood, focusing in that case on new hydrogen pipeline infrastructure. This study also points to the existence of a certain NIMBY effect, as the general acceptance of the technology (hydrogen energy in the energy mix) is higher than the acceptance of hydropower plants (as local infrastructure).

The results from the PCA suggested an eight-factor structure in which the theoretical constructs predicting hydrogen acceptance stand as expected. Thus, the full data could be synthesised in eight new independent components, which is important because it eliminates the possibility of overlapping concepts. Interestingly, environmental and social benefits grouped in the same factor, suggesting that they share important information. As mentioned in Scovell's review [12], despite it being important to consider different types of benefits (e.g., for the environment, for society etc.), our findings showed that the two types loaded together in the factor analysis. The same occurs with risk severity and risk likelihood, which grouped in the same factor. Previous literature has shown that perceived risk is mostly determined by the probability of harm, whereas risk reduction demands are mostly determined by severity of harm rather than probability [64]. Nevertheless, the present research suggests that risk perceptions of hydrogen grouped the perceived likelihood and severity of the consequences together as a unique factor, and feelings or emotions in separate factors. PCA, together with the Cronbach alphas obtained, suggested that the questionnaire used is a psychometrically valid and reliable means of assessing predictors of hydrogen acceptance in Spain.

5.2. Hydrogen acceptance influencing factors

This study also evaluated the capability of eight attitudinal variables (i.e., environmental consciousness, trust in hydrogen technologies, perceived benefits, perceived risks, positive affect, negative affect, objective knowledge, and subjective knowledge), and some demographics (i.e., gender, age, educational level, and income), to predict general acceptance of HET and local acceptance of HRS. It was found that general acceptance of hydrogen was moderately high, and mainly determined by trust in the technology and benefits perception (both for the environment and for society). Environmental consciousness and positive emotions also played an important role. Local acceptance of HRS, which was marginally lower than general acceptance, was mainly explained by positive affect, but perceived benefits and trust in the technology again played a relevant role, together with negative affect and subjective knowledge.

The results from these two predictive models show some similarities and some differences, suggesting that general and local acceptance are separate constructs. While trust in hydrogen technologies, benefits perception, and positive affect are important predictors in both models, environmental attitudes and age are relevant only when considering general acceptance, while negative affect and subjective knowledge are only relevant for local acceptance. Contrary to previous studies [16], risk perception did not appear as a significant predictor in any of the models. These results could also correspond to the low level of implementation of HRS in Spain, with a total of 9, of which only a couple are open to the public. These numbers seem to indicate a very low level of experience, and possibly awareness. Future studies could contrast the results of the present study with a sample of residents in areas where HRS are located in Spain, establishing a relationship between awareness, experience, and risk perception.

The present findings are somewhat in line with previous studies. In general, the present study found three main predictors that have been highlighted previously by other authors. For instance, Häußermann et al. [24] emphasised trust as crucial for green hydrogen acceptance. Social or institutional trust has been shown to influence HET acceptance in many previous studies [21,22,46]. Nevertheless, the present study used trust in hydrogen technologies – also known as confidence in the technology – which has been less studied. Hienuki et al. [65] found that knowledge about hydrogen could lead to improved acceptability of nearby HRS through improved levels of trust in the technology. Our findings confirmed the importance of this construct as the crucial factor predicting HET acceptance and an important one when predicting local acceptance of HRS.

Scovell [12] suggested that its perceived environmental benefits are a particularly strong positive driver of attitudes towards, and acceptance of, HET. Our findings provide evidence that other types of perceived benefits (in our case, social benefits) also help to explain HET acceptance. The review by Scovell [12] also pointed out that affect may be particularly important for explaining HET acceptance at the community and consumer levels. Our study suggests that positive emotions are relevant at both the general and local level, while negative emotions would be of higher importance for the local level. Recently, on this theme, Macht, Klink-Lehmann, and Hartmann [39] showed the important role of affect and perceived benefits in explaining technology acceptance in Germany.

Our results indicate a role for knowledge in hydrogen acceptance both at the general and local level. Several papers have previously discussed the relationship between knowledge and acceptability. For instance, the study by Tarkowki and Uliasz-Misiak [66] stated that knowledge of underground H2 storage is essential for its public acceptance. However, some studies at a more general level claim that there is little relationship between respondents' knowledge and their acceptance [67]. Thus, further studies on this are required for clarification. Additionally, our results show greater support for green hydrogen among citizens who show higher concern about climate change more generally, as previously highlighted by Bentsen et al. [20], and other authors [68,69]. In the case of Spain, Iribarren et al. [36] showed that hydrogen acceptance appeared to be positively correlated with environmental awareness.

Regarding the effect of socio-demographic variables, it was found that only age stands out as statistically significant, having an inverse relationship with general acceptance of HET. This is in line with previous studies, which have shown that age has an impact on hydrogen acceptance in the sense that older individuals are generally less accepting of HET [21,24,30]. Scovell [12] highlighted this as an important consistency. Similarly, Gordon et al. [59] reported that men, younger people, the more highly educated, and those in full-time employment were more likely to be better informed about hydrogen technologies than other socio-demographic groups. Nevertheless, a recent study by Häußermann et al. [24] reported that older individuals were more familiar with hydrogen, whereas younger people were more likely to have heard of green hydrogen.

5.3. Implications, limitations, and future studies

Our study reveals the need to increase hydrogen knowledge among the population by means of effective communication and public participation. According to Astiaso [70], limited knowledge in society might be considered a consequence of a lack of organised education at the primary and secondary level. The study by Alanne [71], with a survey of Finnish energy engineering students, assessed knowledge and perception of hydrogen technology before and after a learning assignment that deals with hydrogen technology. Their results suggested that the students' knowledge and perception of hydrogen technology improved between the pre- and the post-assignment surveys. The biggest changes were seen in their knowledge of hydrogen safety and their willingness to acquire a home hydrogen system. This kind of evidence demonstrates the importance of providing accurate information about hydrogen in order to improve public knowledge and facilitate market acceptance.

The findings also suggest that affect may be particularly important in explaining HET acceptance at the general and the community levels. Thus, it is important to observe how communication campaigns evoke positive or negative emotions among the population. It would be interesting to carry out some experimental research by providing different information to the population and testing its effects on hydrogen knowledge, emotions, and acceptance. In that respect, the study by Hoffman et al. [72] could be a good model. These authors allowed the participants to experience the transformation into a hydrogen economy in a virtual reality scenario. They provided the experimental group of participants with different information about the benefits of green hydrogen as regards the security of energy supply and climate protection. In the control group, they only informed participants about the benefits regarding climate protection. Subsequently, the participants decided on the level of financial support to be given to a specific hydrogen project. Preliminary results showed a higher level of support if the focus was solely on the positive impact of green hydrogen for climate protection.

Local acceptance was assessed among participants from the general population but, in future studies, it should be examined among residents living near existing HRS, in order to obtain more realistic data. Spain currently has 12 refuelling stations: 2 public, 7 private, and 3 under construction [73]. The national strategic plan foresees a significant deployment in the Hydrogen Roadmap with the installation of around 150 publicly accessible hydrogen refuelling stations across the country by 2030 [8]. Future studies could investigate the acceptance of these facilities by local residents, delving into the factors that promote or hinder the acceptance of hydrogen refuelling stations and analysing regional differences. Other relevant and more specific variables, such as place attachment or distributed fairness, could have a role when assessing local acceptance in real sites. In a case study of a hydrogen pilot plant in the Canary Islands (Spain), Farràs et al. [74], stated that islanders, and visitors to the islands, have a deep connection to nature and green initiatives that was experienced more immediately than on the mainland. They noted that in the Canaries, as in other island locations, a decisive factor in support for the project was its promise to meet the requirements for local, and in part environmentally friendly, tourist transport.

There may be some methodological limitations, such as the potential bias associated with the use of self-reported measures. However, social desirability was counterbalanced by anonymity and by the fact that there is no financial or other reward to encourage particular responses. Other potential biases associated with online surveys were counterbalanced through the use of a quota sample (for example, the potential bias associated with a higher response rate from those who are more active on the internet, i.e., probably the youngest). Although the sample size of this study is sufficient to ensure statistical validity [75,76], future research could enhance the generalizability of the results by employing stratified random sampling with a larger representative sample from the country.

This study analysed data collected at the individual level. According to Steller (2024) [77], most research on the social acceptance of hydrogen focuses on individual-centered influences, suggesting that acceptance of the technology requires resolution at this level. However, future models should aim to incorporate contextual factors more comprehensively, moving beyond solely individual-centered approaches. In future studies, it would also be interesting to combine qualitative and quantitative methods. As stated by Zaunbrecher, Arning & Ziefle [78], this combination of methods is interesting in detecting effective acceptance drivers. Accordingly, we quantitatively measured three positive and four negative emotions, but it would have been relevant to previously assess potentially different emotions from HRS residents, using qualitative methods. Future longitudinal studies would benefit from exploring the well-known gap between self-reported data and actual behaviour.

6. Conclusions

This study contributes to the literature on public acceptance of hydrogen technologies and hydrogen fuelling stations, comparing different acceptance types (general and local) in Spain, where there has been significant deployment of the technology over the last 10 years. We emphasise that trust in the technology, perceived benefits, and affect are key determinants for acceptance of the technology, both at the general and the local level. When it comes to the general level, other aspects need to be considered also, such as environmental consciousness, knowledge, or age. Considering that the understanding of public acceptance of HET is a key issue for its deployment, analysing the predictors of acceptance might be very relevant for policy setting and useful for the market sector as well. Moreover, this study aims to highlight the relevance of social variables during the development of hydrogen technology in Spain, with clear implications for society, stressing the evident need for more inclusion and participation in the development process, in order to make it more effective in the long term.

CRediT authorship contribution statement

Roser Sala: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lila Gonçalves:** Writing – review & editing, Writing – original draft, Conceptualization. **Ning Huan:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Hitomi Sato:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Toshiyuki Yamamoto:** Writing – review & editing, Supervision. **Yin Haohui:** Writing – review & editing, Investigation. **Dimitrios Tzioutzios:** Writing – review & editing, Methodology, Conceptualization. **José-Blas Navarro:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation.

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

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