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Stakeholders' perceptions of hydrogen and reflections on energy transition governance

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Abstract

Background There is a race to innovate, develop or create hydrogen production technologies to accelerate energy transition and create a hydrogen economy. Acceptance has been used in social science literature as a lens through which to anticipate possible challenges surrounding hydrogen technologies. However, very few studies problematize perceptions and focus on the production of hydrogen. Hence, this study aims to bridge these theoretical and empirical gaps using a mixed-method approach based on semi-structured interviews ($n = 7$) and a questionnaire survey ($n = 73$) to understand stakeholders' perceptions of hydrogen production sources through a social construction of technology lens.

Results The findings suggest a tendency to favor hydrogen produced from renewable sources and to reject hydrogen produced from non-renewable sources. All the examined groups conform to this pattern. Their perceptions are based on prior knowledge of hydrogen technologies, with participants seeking information from specialized sources or from activities promoted by their organizations. Participants anticipate that hydrogen will be generated primarily through renewable energy sources and utilized where direct electrification is unfeasible. In addition, they envisage that the hydrogen economy will enhance energy democracy through representative participation in decision-making. Nevertheless, it is acknowledged that the topic is limited to certain social groups and kept away from the public eye. Furthermore, unlike the benefits, the perception of risk appears to have no impact on perceptions' construction. High confidence in science appears to minimize the recognition of potential risks and bolster the recognition of potential benefits. There is, however, a lot of uncertainty about the possible real impacts of the hydrogen economy.

Conclusions There appears to be a collective perspective on hydrogen production sources, indicating the existence of social representations. Nevertheless, group attitudes and backing towards hydrogen vary. The participants identify hydrogen as a matter that remained unnoticed for over a decade, despite its prominent position in the policies and economic approaches of numerous countries. The topic has been relegated to third parties. This exclusion of civil society from decision-making may justify the NGO group's critical stance towards hydrogen. Moreover, it suggests that energy democracy, which is based on information dissemination and participation, is not being achieved.

Keywords SCOT approach, Hydrogen, Perceptions, Mixed approach, Stakeholders, Governance, Energy transition

Background

The world today faces multiple challenges and risks at different scales. Since the dawn of the Industrial Revolution (eighteenth century), man-made activities have required an increase in energy production and use, causing an exponential rise in carbon emissions that leads to catastrophic risks for the environment and societies [1]. It is widely known that climate change is related to the

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concentration of greenhouse gases (GHGs) in the atmosphere, usually emitted by the combustion and use of fossil fuels, which alters the earth's energy balance [1]. Thus, a sustainable energy transition is required, which involves shifting from a system heavily dependent on fossil fuels towards a more varied range of energy sources, especially reliant on renewable energy. This places hydrogen as a promising energy carrier at the forefront of technology development and international policymaking [2]. However, as stated by Sovacool [3], there is no magic formula for energy transitions, since each country and region has its own strategies according to the availability of its natural resources and its political and sociocultural contexts. This results in diverse paths and dynamics with different times and cost/benefit allocations among homeowners, consumers, corporations, governments, and other parts of society [3]. Transitions can embody or trigger social injustices from local to international levels [4, 5], especially when there is no vigilance, i.e., democratic participation [6].

International policies and agreements are in place, in which several countries have committed to achieving carbon neutrality by 2050 (for example, the Kyoto Agreement (1997), the Paris Agreement (2015), the Climate Act (2021), and the recent *Fit for 55* package (2021)). Furthermore, several factors have triggered the need to find low-cost alternatives to fossil fuels and, consequently, bolster the race for technological innovation. These include the post-COVID-19 context, which places countries and people in situations of social and economic vulnerability. Therefore, "significant shares of countries' stimulus funds have been earmarked for hydrogen projects, bringing hydrogen into the realm of geoeconomic competition." [7]. Moreover, the ongoing Russo-Ukrainian war has jeopardized energy security concerns in countries reliant on Russian natural gas, which has prompted the recent energy crisis [7, 8].

It should be noted that the potential of hydrogen is not a novelty of the twenty-first century, as it has been used in certain industrial sectors (e.g., petrochemicals, refineries, etc.) for over 100 years [9]. Moreover, hydrogen has been regarded as a viable path for the energy transition since the 1970s oil crisis, but it has yet to gain ground [10–12]. The costs and/or the lack of technologies for large-scale hydrogen production are the main obstacles, since hydrogen is not available in its "pure" state and primary energy is required to extract it [2, 10, 13, 14]. Nevertheless, hydrogen has featured on the political and scientific agendas in the last decade [12]. In 2017, Japan emerged as the first country with a national hydrogen strategy. However, by 2022, more than 30 countries across all continents had launched or were preparing their own strategies [7]. Therefore, significant efforts have been made to innovate or improve existing technologies to create a hydrogen market/economy (see [15]), but there are still limitations to overcome at economic, legislative, political, social and technical levels [13, 16–19].

When discussing hydrogen technologies, the focus is primarily on the technologies linked with producing, storing, and distributing hydrogen. According to van Renssen [20], there are four main types of hydrogen production. Each type is associated with a different color depending on the method of production: (i) gray hydrogen (currently the most used in industry, but its production is derived from fossil fuels, therefore, contributing to CO_2 emissions); (ii) blue hydrogen (produced from natural gas, but with CO_2 capture and storage); (iii) green hydrogen or renewable hydrogen (produced through water electrolysis from renewable sources); and (iv) turquoise hydrogen (produced from methane pyrolysis). Although the agendas aspire to the predominance of hydrogen produced from renewable sources, according to the latest IEA annual report for 2022 [8], less than 1% of the hydrogen produced in 2021 was clean hydrogen, even if there is growth in this direction (a 20% increase in 2021 compared to 2020).

This study was carried out under the European Union-funded 112CO2 Project, which seeks to create an innovative method for the production of low-carbon hydrogen through methane decomposition at low temperatures, whereby the carbon is converted to a solid state (turquoise hydrogen). As such, this article is focused on hydrogen production sources (HPSs). Owing to the wide range of methods and technologies available for producing hydrogen, this paper focuses only on distinguishing between hydrogen produced from renewable (green) and non-renewable (non-green) sources, a distinction that is crucial as it significantly affects what the hydrogen economy will entail, and its associated consequences [21].

There is a discernible tendency towards conducting social analyses of perceptions and acceptance of hydrogen technologies [22–37]. However, the mode of production and distribution of hydrogen has been largely neglected in social analyses, despite the considerable attention paid to its uses and applications in the existing literature [2, 37]. It follows that an important aspect has been overlooked, since "the choice of hydrogen production technology determines the cost and carbon emissions of hydrogen energy" [17]. Moreover, most of the studies lack a theoretical framework and are mainly focused on social psychological perspectives [37].

Based on the premise that technology acceptance or rejection is rooted in social interpretation that results in perceptions [38, 39], the purpose of this study is to fill the gaps in theory and empirical evidence by providing insights into stakeholders' perceptions of HPSs through a sociological perspective based on the social construction of technology approach. It seeks to comprehend the perceptions of hydrogen as predispositions to acceptance or rejection, as well as reflect on how structural factors may be linked to stakeholder's interpretations. Thus, our aim is to answer the following research questions:

1. What are the perceptions of stakeholders regarding hydrogen?
2. How are stakeholders' perceptions constructed?

Literature review

Social construction of technology approach

Within the Sociology of Technology, there are two opposing approaches: the technological determinism and the social construction of technology (SCOT) [40]. For the deterministic approach, the main argument is that society and technology are two separate spheres, and that technological change occurs independently of social and cultural aspects [41]. Technology, as a neutral product, is, therefore, autonomous and plays a crucial role in social development. Critical of technological and economic determinism, the SCOT perspective argues that technology as a culturally constructed artifact, i.e., a man-made construction [41], is bound and shaped by the social, economic, political, and cultural environment in which it is situated. Technology is thus seen as a product of human action and social interpretation. However, social constructivists do not deny the causal relationship that technology may have in shaping society but argue that the two are mutually constitutive.

Pinch and Bijker [42] proposed the SCOT conceptual framework for the analysis of technological and innovation processes in the 1980s, using an ethnographic methodology. The authors outlined five main interrelated components of SCOT, namely: interpretive flexibility, relevant social group, technological frame, closure and stabilisation, and wider context. The concept of interpretive flexibility suggests that technology design and development is an open process that can produce different outcomes due to the multiple interpretations and meanings that social actors can attach to the artifacts. Consequently, this element implies the analysis of discourses to extract the perceptions of the relationship between social actors and technology.

According to the authors [42], the concept of a relevant social group is linked to the embodiment of certain interpretations and suggests that "all members of a certain social group share the same set of meanings, attached to a specific artifact". Thus, the process of technology development involves friction, negotiation, and consensus, as multiple social groups may embody different interpretations and interests of a particular technology [40]. In this sense, it is crucial to identify and consider which social groups social actors are involved in.

In short, technology development depends on power relations and social dynamics between and within social groups, where some can influence the final decision about a technology and whether a particular technology is accepted or rejected. This is linked to the other element of the SCOT framework, which relates to the technological frame, a concept which suggests that a collective interpretation of an artifact is created when a group begins to interact around it, sharing "some common characteristics in the way they perceive an artefact and attribute meaning to it" [43]. When the relevant social groups agree on a solution to a technology problem, and it is perceived as being solved, the technology reaches the stage of closure and stabilization [44]. Pinch and Bijker [42] suggest that closure can occur through rhetorical and redefinition mechanisms. However, this is a non-linear process that involves conflicts of interest and controversies in imposing a dominant vision [45].

The SCOT approach has been criticized for its concepts, methodology, ontological position, and historical accuracy, as well as its political, ethical and normative stance [43]. Some critiques towards the original approach are related to its failure to consider the temporal and socio-historical context preceding a technology's emergence. Moreover, there has been criticism of the overemphasis on the individual and disregard for the constraints imposed by the social structures, including social group backgrounds and power imbalances within and between them, all rooted in structural features of social life [40]. As has been noted by some authors [46, 47], decision-making involvement in technology is not equally distributed, with some groups or elements being entirely excluded. It is important to consider the presence of social inequalities in the technology and innovation fields. Therefore, it is crucial to address this issue in the context of energy transition and hydrogen.

These criticisms have unveiled new avenues for analysis and reinforced the approach with novel elements, concepts, and techniques. By employing this approach, we aim to explore what lies beyond the boundaries of perceptions of HPSs.

The role of perceptions on hydrogen acceptance or rejection

The successful implementation of hydrogen technologies depends on political decisions, markets and, ultimately, the stakeholders and public acceptance towards emerging technologies [48]. According to Schönauer and Glanz [49], acceptance or rejection is subject to individual or group interpretation and is manifest through behavior. That leads, in line with Bharadwaj et al. [14], to an active ("which may include specific actions, engagement or forms of participation via citizen initiatives") or passive acceptance ("where there is no active resistance"). Furthermore, acceptance or rejection is rooted in perceptions. Ultimately, perceptions and behaviors are shaped by the attitudes and subjective norms of social actors [50].

Social science studies have covered hydrogen acceptance and explored the factors that may be related and influence perceptions [37], namely, sociodemographic and organizational aspects, expectations, technological imaginaries, knowledge, and subjective stance [37].

Sociodemographic factors seem to play a crucial role in shaping perceptions and acceptance beyond contextual factors. Research suggests that younger, highly educated male participants tend to be more accepting of hydrogen technologies [51, 52]. However, there is some discrepancy in the findings about the importance of sociodemographic factors in perceptions' construction [37].

Furthermore, the source of hydrogen production seems to impact the acceptance or rejection of technologies, with greater acceptance of hydrogen produced from renewable sources. Bentsen et al. [53], reveal that public support for blue and gray hydrogen amongst Norwegians decreased upon knowing that these hydrogen production sources are derived from coal, oil, or natural gas. The authors [53] further recommend that governments and technology developers prioritize transparent communication about hydrogen production methods to prevent distrust and potential public backlash.

Upham et al. [54] have illustrated that shared expectations and social representations about hydrogen technologies fluctuate in communication processes through rhetoric.

Moreover, the authors [54] assert that technological expectations are influenced by the sociotechnical, cultural, political, economic, and organizational context within which actors operate. In other words, stakeholders' perceptions are constantly shaped, namely, by the political, corporate, scientific, and public imaginaries about technologies, which may focus more on their benefits or risks [16, 18, 55–59].

Previous studies have indicated that perceived risks can have a negative impact on acceptance, outweighing the potential benefits [37, 60]. A literature review by Scovell [60] found that the inclusion of risk perceptions has increased since 2016 in studies on the acceptance of hydrogen, especially on its use in vehicles [30]. However, according to the findings of Ricci et al. [23], the concept of "public acceptance" goes beyond risk perceptions, encompassing broader issues of context, environment, and the relationship of hydrogen to energy. In addition, studies indicate a strong positive correlation between the acceptance of hydrogen by individuals and its perceived benefits, despite low levels of knowledge [23, 37, 60, 61].

Sherry-Brennan et al. [61] contend that it is necessary to understand the public's perceptions in order to understand why they tend to have positive attitudes towards hydrogen, despite their lack of knowledge on the matter. The authors [61] used the theory of social representations of hydrogen and show that scientific knowledge, common sense, and emotions are involved in these representations, concluding that knowledge per se is not predictive of support for hydrogen. On this line of thought, perceptions can be mainly based on inductive factors [62]. Several studies have noted the importance of subjective stance on perceptions and, subsequently, on acceptance and rejection of a technology. Among this dimension, positive attitudes towards hydrogen and high environmental concerns are indicated as strong predictors of acceptance and of a supportive behavior [63].

Understanding the relationship between these variables in shaping stakeholder perceptions of HPSs is, therefore, crucial. Nonetheless, only a limited number of studies have been dedicated to investigating this relationship (e.g., [35, 64]).

Methods

Methodology

Bearing in mind the context and aims of this study, our methodological approach comprised two main stages: (1) identification of potential stakeholders to be consulted; and (2) eliciting their perceptions through semi-structured interviews and questionnaire survey. We employed a convergent and mixed methodological strategy to address our research questions. To ensure triangulation of data, we utilized corresponding dimensions and categories in both qualitative and quantitative phases. Table 1 summarizes the included dimensions, namely, sociodemographic characteristics, organizational level, expectations, technological imaginaries, knowledge and subjective stance. On one hand, qualitative methods provide a deeper understanding of the dimensions under analysis [65]. On the other hand, quantitative methods allow a great number of social actors from diverse groups to be reached and the analytical dimensions to be measured, strengthening the analysis.

We assume that the construction of perceptions results from the relationships between the dimensions and subsequently their categories identified in Table 1.

Stakeholder's identification and categorization

Stakeholders are individuals or groups who may have any kind of participation or interest, i.e., a "stake", in a situation, project or organization. This study takes the concept of external stakeholder proposed by Freeman [66] as its

Table 1 Dimensions, categories and indicators included in the semi-structured interviews and questionnaire survey

Dimensions	Categories	Indicators	Dimension description
Sociodemographic characteristics	Gender	Male, female, other	Characteristics of social actor regarding gender, age and educational attainment level
	Age	Age number	
	Educational level	Before tertiary education; undergraduate degree; master's degree; doctorate/post-doctorate	
Organizational level	Country	Country's name	Organizational context to which the social actor belongs, including the country of their organization, the group that is associated, and the organization's concerns and actions towards energy transition and hydrogen
	Group	NGO; Political Sector; Associations; Mass media; Hydrogen Consumers; Solid-State Carbon Consumers; Non-profit Research Centers; Other	
	Organizational sustainability awareness	Concerns; actions	
Expectations	Governance	Public participation	Expectation is a belief about what might happen in the future
Technological imaginaries	Perceived benefits	Technical; environmental; economic; social	The risks and benefits associated with hydrogen technologies
	Perceived risks	Technical; environmental; economic; social	
Knowledge	Familiarity	Hydrogen types; policies	Knowledge is defined as the degree of familiarity and proximity to energy transition and hydrogen issues
	Sources of information	Specialized, non-specialized and institutional sources	
	Trust	Media; policy decision makers; science	
Subjective stance	Attitudes	Positive; negative; neutral	Refers to the positive, negative, or neutral subjective assessment towards overall hydrogen and hydrogen source of production
	Financial support	Positive; negative; neutral	

reference, understood as any group or individual external to the 112CO2 project that can affect or be affected by the achievement of the project's goals. In this study, the only criterion considered for identifying and consulting with stakeholders was their involvement in the energy sector.

To mitigate potential biases in the sample, we employed three techniques to identify stakeholders. Initially, an informative survey was conducted among internal project partners from January to April 2022 to gather the names and contacts details of potential external stakeholders, resulting in the identification of 46 external stakeholders. Subsequently, we carried out further research by searching the list of projects funded by the European Climate Initiative (EUKI) on the Internet. A wider range of stakeholders was identified through this further search. A total of 305 stakeholders, largely associated with non-profit entities, such as NGOs, associations, foundations, and non-profit research centers from 32 countries, were identified. In addition, the interviews and survey also led to snowball sampling to identify a further 62 stakeholders who were then sent a hyperlink to complete the questionnaire survey. In the end, our database contained 367 identified stakeholders.

To identify the potential stakeholders, we considered 15 categories. The categorization was determined by authors, *à posteriori*, based on the information available from each stakeholder website. The classification had the following criteria: public/private; profit/non-profit; relationship with hydrogen field; relationship with academia; and mass media. For the category "others" the information available was not conclusive according to our criteria.

Despite the effort, only 80 stakeholders were consulted, 7 through interviews and 73 through an online survey. This limitation could be explained by the team's limited resources and reflects the challenge of reaching key informants.

In the following sections, the stakeholders who participated in the interviews are referred to as "interviewees" (I) and those who responded to the survey are the "respondents".

Semi-structured interviews

To account for the subjective dimension associated with the object of study, 13 stakeholders in Portugal belonging to the groups labelled "associations" and "non-governmental organizations" working in the field of energy and/or hydrogen were contacted between April and June 2022 to conduct semi-structured interviews via Zoom or Teams. The selection of stakeholders was limited to Portugal, the country that coordinates the research, due to resource limitations. These stakeholders can play relevant roles in civil society, particularly: organize interests clearly; make political and authorities' actions susceptible to scrutiny; establish bonds of trust with citizens; and foster more inclusive, rational and deliberative public debates [67]. Another justification for using the label "associations" is related to the fact that these stakeholders represent others listed in our database. We were able to conduct interviews with 7 of the 13 stakeholders contacted.

The semi-structured interview guide[1] was built on the basis of open questions to analyze the subjective issues and social constructions regarding the energy transition, hydrogen and HPSs. Therefore, this type of interview is flexible and allows the information deemed relevant to be captured [65].

The interviews totaled approximately 5.7 h, corresponding to an average of 49 min per interview. They were partially transcribed, and the data were analyzed using the qualitative content analysis, "as a research method for the subjective interpretation of the content of text data through the systematic classification process of coding and identifying themes or patterns." [68]. The coding process had as its unit of analysis the predefined dimensions (see Table 1).

Questionnaire survey

To reach more stakeholders from other groups and countries, as well as to complement the qualitative analysis, a questionnaire survey was developed by the authors through Google Forms format. It consisted of 19 questions most rated on a 5-point Likert-type scale to measure stakeholder's expectations, knowledge, technological imaginaries, and subjective stance towards hydrogen and, specially, HPSs.[2]

The instrument was validated by peers and by internal partners of the 112CO2 project. The questionnaire was sent by email to all stakeholders in our database ($N=305$) between July and December 2022, with follow-up emails every 2 weeks. Only 52 stakeholders answered the survey, which may reveal the difficulty in contacting stakeholders involved in the hydrogen economy, as it is not yet a stabilised field compared to the wind industry, for instance. To gather more responses, the team shared the questionnaire survey on the 112CO2 project's social media (namely, LinkedIn, Instagram, Facebook, and Twitter) between October and December 2022, gathering 21 additional responses. This, in turn, affected the data collected, since the authors did not control who had access to the project's social media and, therefore, who the respondents were.

The data were analyzed using IBM SPSS Statistics software, which facilitated the performance of uni- and bivariate analyses, as well as nonparametric tests. The purpose was to ascertain inter-relationships between the analyzed dimensions and to test for variations among different stakeholder groups. Initially, a Cronbach's Alpha reliability test was conducted to determine whether the analyzed items could be clustered into a single scale (see Additional file 1). Furthermore, after conducting scale reliability tests, a nonparametric Kendall's Tau-b correlation was used to examine only the associations between the variables of hydrogen source production and hydrogen subjective stance (see Additional file 2). The subjective stance comprises attitudes and support. This test was selected because our sample size is small and does not follow a normal distribution, as indicated by Shapiro–Wilk test p values lower than 0.05 (i.e., $p= <0.001$), and because we are using ordinal scales.

In order to understand whether there are differences between the groups of stakeholders in our sample, we performed the Kruskal–Wallis test, a non-parametric test that serves to assess the differences among three or more independent groups [69]. It is particularly important to determine whether there are differences regarding perceptions of hydrogen among groups. To determine group differences, an independent samples non-parametric test was conducted (see Additional file 3). Due to a minimal number of elements in some groups ($n=3$), the analysis will only be performed on the variations between NGOs, the political sector, hydrogen consumers, and non-profit research centers. While the "other" group has an adequate number of elements for the test ($n=11$), we will exclude it from analysis due to the unknown stakeholder involvement. Non-parametric tests were carried out to investigate differences in subjective attitudes towards hydrogen by gender, age, education and country (see Additional file 4).

It is also important to acknowledge the need for further analysis for a more comprehensive and robust examination of the issues in question. Nevertheless, this research has an exploratory nature, and the data gathered does not permit in-depth analysis. Although our sample is not representative and does not allow generalizations, the results are still relevant and important to bridge scientific literature.

Results

Sociodemographic characteristics

Table 2 provides summary information regarding the sociodemographic characteristics of the interviewees and respondents ($N=80$).

Nearly all stakeholders (approximately 97%, $n=78$) hold a bachelor's degree or higher. In addition, roughly

[1] The interview guide is available upon request.

[2] The data collection instrument is available upon request.

Table 2 Sociodemographic characterization of the interviewees and respondents

	Interviews *n*	Questionnaires *n*
Gender		
Male	7	50
Female	0	23
Total	7	73
Age		
< to 35	1	23
36–45	1	23
46–55	2	13
56–65	2	13
More than 66	1	1
Total	7	73
Educational attainment level		
Before tertiary education	0	2
Undergraduate degree	2	5
Master's degree	4	40
Doctorate/Post-doctorate	1	26
Total	7	73

Table 3 Institutional affiliation of the interviewees and respondents

Institutional Belonging	Interviews *n*	Questionnaires *n*
NGO	1	16
Political Sector	*	6
Associations	6	2
Mass media	*	1
Hydrogen Consumers	*	3
Hydrogen Producers	*	1
Solid-State Carbon Consumers	*	1
Non-profit Research Centers	*	32
Other	*	11
Total	7	73

*No interviews were conducted

71% ($n = 57$) of stakeholders identify as male, potentially reflecting persistent gender inequality in the energy field. The average age of interviewees and respondents is 53 and 43 years, respectively, with the median age closely aligning with the corresponding averages.

Organizational level

Regarding the organizational level, most of the stakeholders are affiliated with NGOs and to Non-profit research centers (see Table 3) especially in Portugal, Germany, Spain, Hungary, and Poland (see Table 4).

Table 4 Country of institutional belonging of the interviewees and respondents

Country	Interviews *n*	Questionnaires *n*
Germany	*	6
Germany and South Africa	*	1
Austria	*	1
Bulgaria	*	3
Czech Republic	*	1
Croatia	*	1
Slovakia	*	1
Slovenia	*	3
Spain	*	5
Estonia	*	3
Europe	*	1
Greece	*	1
Hungary	*	4
India	*	1
Lithuania	*	1
Poland	*	4
Portugal	7	29
Qatar	*	1
Romania	*	5
Serbia	*	1
Total	7	73

*No interviews were conducted

To bring these issues into the public eye, all the interviewees state that the institutions to which they are affiliated carry out activities that mainly involve promoting debates among social actors capable of monitoring and influencing political actions. Regarding the hydrogen agenda, 5 of the 7 interviewees revealed that their organization tended to promote activities that are directly related to this emerging issue, where strategies and political decisions are discussed, and the benefits and ambiguities of this energy paradigm are pointed out.

The survey data also shows a concern with efforts to move the energy transition forward, with most respondents stating that their organizations/companies are concerned about energy transition issues (~85%, $n = 62$) and promote actions for this purpose (~86%, $n = 63$), as shown in Fig. 1.

Expectations

All interviewees thought that energy transition is inevitable, although they recognize that it remains "*complicated*" (I1) and a "*demanding problem*" (I7), which involves "*different perspectives*" and "*asymmetries*" (I2). Thus, the transition should also "*prioritize direct and indirect renewable electrification*" (I4) and provide "*on the*

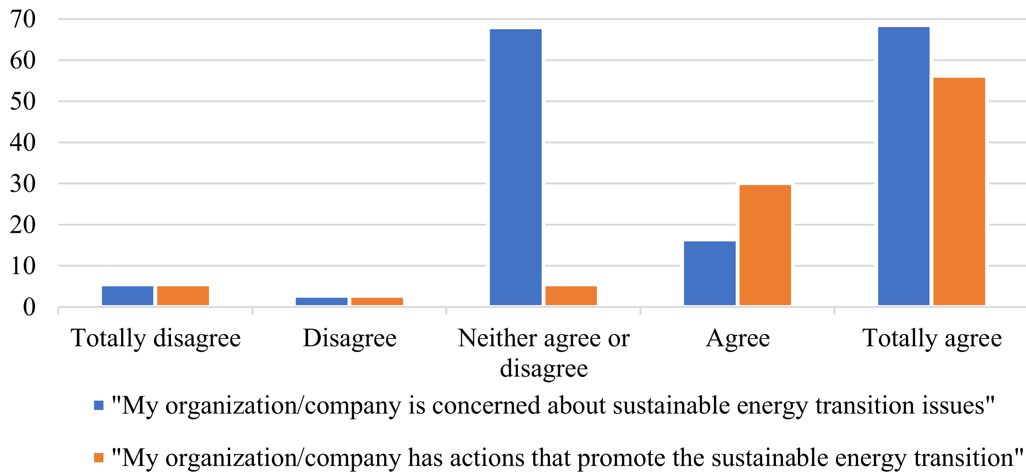

Fig. 1 Degree of organizational sustainability orientation (%, $n=73$)

part of public policies, the necessary signals for decarbonization to happen" (I5). From a different perspective, there is an argument that fossil fuels are essential for the energy transition process due to the absence of viable alternative technologies and to ensure the supply of energy:

> *"We are in fact witnessing an evolution and the trend is for this evolution to be more accelerated and we still think it should be a transition and not disruption. (...) [but] I can't stop using energy sources that today we consider polluting, (...), but which are essential (...) as long as we don't have any alternative forms." (I6).*

Therefore, according to certain interviewees, political powers must scrutinize various approaches towards the energy transition meticulously in order to "*make use of all possibilities*" (I2). However, the main expectations fall on renewable energy sources.

The interviewees expect that besides electrification, renewable energy usage and political responsibility, other environmental and social issues should also be considered. Therefore, it is stated that the energy transition should be conducted in an "*integrated*" (I6) and "*fair manner*" (I3), guided by the notion of energy justice and citizen involvement. The energy transition is expected to foster the transformation from a vertical model to a decentralized model of electricity production and consumption, "*where consumers can be producers and* vice versa" (I3), that is, energy democratization.

Hydrogen is considered a promising alternative for sectors where electrification is not feasible, according to the interviewees. However, all interviewees envisaged the utilization of hydrogen generated from renewable energy sources, namely, green hydrogen. Nonetheless, it is expected that the exclusive focus will not be on green hydrogen, considering the potential risks inherent in such a decision. There is a need to consider alternative technologies that have the potential to offer additional advantages, especially due to the limitations of green hydrogen to scale up.

The interviewees also expect: the development of public policies; an increase in the production of renewable electricity for green hydrogen production; a decrease in hydrogen production costs; the creation of economic mechanisms; the creation of a market; large investments in hydrogen projects and restructuring of the infrastructure for its introduction; and greater involvement of civil society in this matter, since it has been left to third parties, such as energy corporations and policy makers.

> *"I think hydrogen is our future, there will have to be major investments in optimizing its production, its handling, the introduction of a system when we talk about pipelines, its use for other purposes ..." (I7).*
> *"Well, because in fact one thing we see is that hydrogen (the way it's being introduced) goes through the same players as always (...) [it is necessary] to create a European network of civil organizations, which can in some way serve to strengthen the participation of civil society in the hydrogen debate." (I5).*

Converging with the expectation of democratizing the energy system, respondents gave their opinion on the importance of involving various social actors in hydrogen decisions, considering it "important" or "very important" to involve all actors, although they prioritize the participation of scientists, politicians, and entrepreneurs (see Fig. 2). The data demonstrates that respondents from diverse groups and nations aspire towards participatory governance.

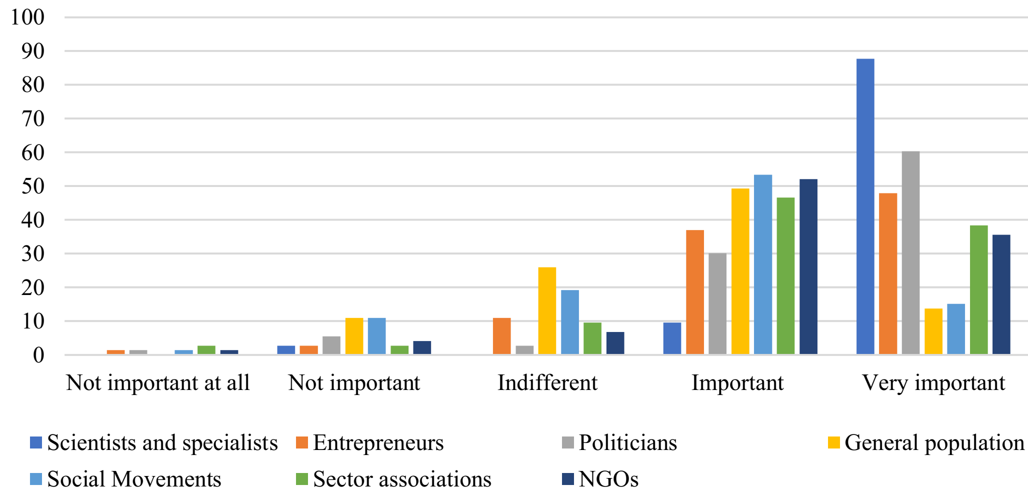

Fig. 2 Degree of importance of participation of various stakeholders in decisions about hydrogen (%, $n = 73$)

Table 5 Benefits and risks perceived by the interviewees

Perceived benefits	Perceived risks
Economic benefits Creation of a new value chain Competitive cost (green H2) Use of existing infrastructures	Economic risks Large investment and uncertainty Energy dependency (if countries must import, for instance, natural gas for hydrogen production)
Technical benefits Flexibility of use (various sectors where electrification is not possible) Storage capacity Solution for the decarbonization of sectors that are difficult to electrify Increasing the security of the energy system	Technical and technological risks Technical and human failures Implementation of technologies Handling of hydrogen Accidents Transport
Environmental benefits Replacement of fossil fuels in industry and mobility as a clean fuel Decarbonized/clean and inexhaustible energy carrier Possibility of being produced in a green and environmentally clean way The ability to provide clean energy without emitting pollutants, producing only water vapor	Environmental risks Resource scarcity Impacts on biodiversity
	Social risks Public concerns Conflicts of interest Dependence on political will Misinformation Creation of new needs Territorial occupation without defined criteria Non-efficient use of hydrogen

Technological imaginaries

The current dimension is assessed on the basis of the benefits and risks that stakeholders attribute to hydrogen technologies. The question of the benefits and risks of the hydrogen agenda is very present in the interviewees' answers. As we can see in Table 5, benefits essentially have to do with economic, environmental, and technical benefits (for more details see Additional file 5).

The benefits are primarily in relation to the notion that hydrogen is a clean energy carrier that can facilitate decarbonization due to its unique properties. Only hydrogen produced from renewable sources was discussed when the topic of hydrogen benefits was raised. According to the interviewees, the hydrogen molecule has several important properties, such as its inexhaustibility, storage capacity and the ability to provide clean energy without emitting pollutants. As such, it can foster the decarbonization of several sectors where direct electrification is not possible, thus representing a possible replacement for fossil fuels. The consequent benefits are related to the possibility of strengthening and complementing the national energy system at the level

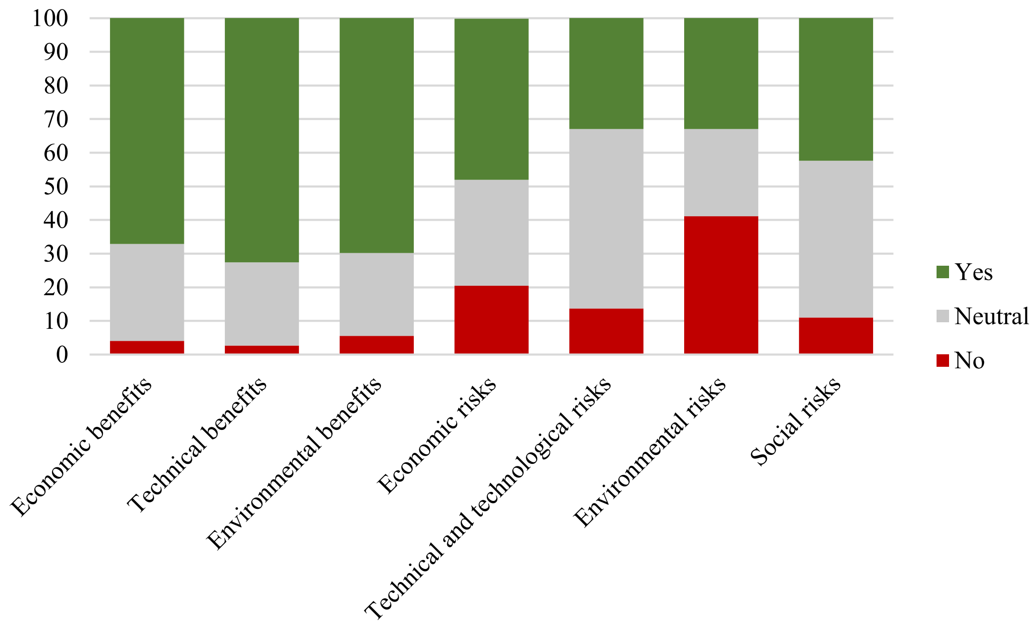

Fig. 3 Benefits and risks associated with hydrogen by respondents (%, $n = 73$)

of renewable energies, increasing the security of energy supply, and creating a value chain with (green) hydrogen production at competitive costs.

In turn, there was some difficulty in identifying the risks of hydrogen. Even so, interviewees identified risks characterized as being the product of human action, namely, technical, social, environmental, and economic risks.

The risks primarily stem from the outcomes that can result from hydrogen strategy decision-making, specifically the absence of transparency in the processes. This could potentially lead to conflicts of interest and misinformation. In addition, there is a danger of ineffective hydrogen utilization if countries prioritize exports over domestic supply.

Concerns have been raised regarding the production of hydrogen through renewable energies and fossil fuels in the context of HPSs. One concern is the potential requirement for a substantial expansion of renewable energy megaprojects to meet the demand for hydrogen, which may result in detrimental consequences on biodiversity (such as bats), landscapes, or even prompt newly emerging needs arising from water consumption for electrolysis. Another issue is about the production of hydrogen from fossil fuels as this may perpetuate energy dependencies and the associated social, economic, political, and environmental implications, including resource scarcity and public opposition.

The quantitative data aligns with the qualitative results. More than 50% of survey respondents agree that hydrogen has environmental, technical and economic benefits (see Fig. 3). However, there is a stronger perception that environmental risks are minimal, while technological risks are uncertain and economic and social risks are ambiguous.

Despite potential risks, interviewees and respondents expressed low concern regarding hydrogen due to their belief in its benefits. In addition, stakeholders assume that science can mitigate the potential risks, stating that risks are acceptable for future generations.

Knowledge

During the interviews, stakeholders said that discussions about hydrogen are recent, and limited to certain groups. There remains a significant lack of knowledge about hydrogen and its technologies, particularly among members of the general public (I1, I5, I7). The distancing of the public from the topic can be attributed to its technicality as well as the limited promotion and discussion in the media. In addition, the lack of direct impact of hydrogen technologies on everyday life is considered a contributing factor (I1, I3). The survey findings are consistent with those expressed by the interviewees. Over 70% of the respondents reported their disagreement with the statement, "Hydrogen is a well-known topic in my country".

As our sample consists of stakeholders who are relatively close to hydrogen issues, it is not surprising that the level of knowledge about hydrogen is relatively high. The survey data shows that the respondents are familiar with

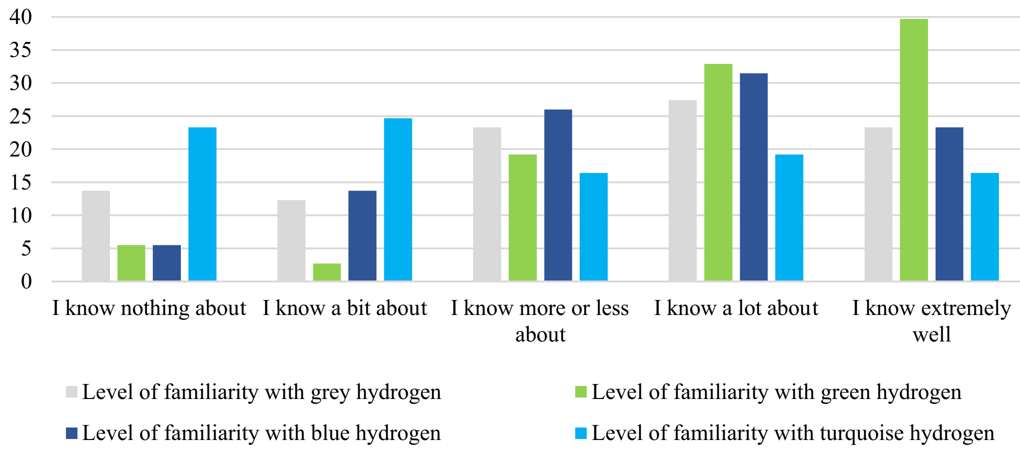

Fig. 4 Respondents' level of familiarity with hydrogen types (%, $n = 73$)

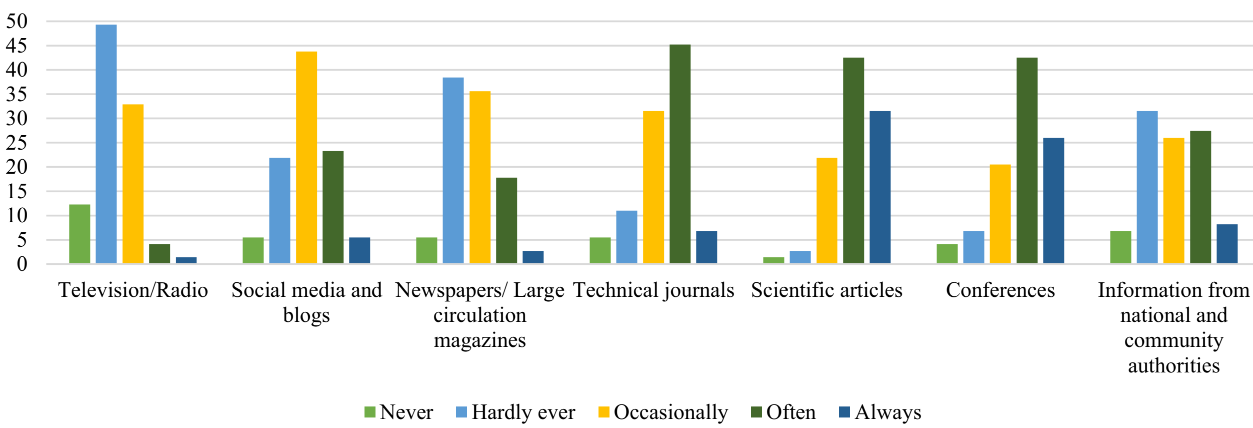

Fig. 5 Frequency with which respondents seek information about hydrogen from various sources (%, $n = 73$)

HPSs, with almost 30% ($n = 21$) having "some knowledge" and almost 55% ($n = 40$) being "well or extremely aware" of them. Specifically, the data indicates greater knowledge of green hydrogen, followed by blue hydrogen and gray hydrogen. However, there is less familiarity with turquoise hydrogen, which is produced by methane decomposition (see Fig. 4). Based on this, we can assume that perceptions about hydrogen and HPSs have some sort of factual basis.

Moreover, although there has been a development in the policy agenda for hydrogen, a vast majority of respondents (56.2%, $n = 41$) displayed minimal knowledge of both national and international public policies regarding hydrogen.

In our quest to discover sources of information on hydrogen, we observed a pattern in the sources that respondents utilized to access information on the subject (refer to Fig. 5). Scientific articles, conference papers, technical journals, and information disseminated by national and European Union authorities were cited as preferred sources for gaining insights about the hydrogen agenda, whereas general media channels were less frequently used. Similarly, interviewees considered that the mass media seldom provides information about this energy paradigm. As such, they acquire knowledge about hydrogen issues primarily from organization-promoted debates and events and scientific articles.

We aimed to evaluate the reliability of the media, political decision-makers, and science in their respective roles of reporting news, making decisions, and finding solutions. Our analysis focuses on the level of trust that stakeholders place in these entities. Regarding trust in the information provided in the media about hydrogen, almost 50% ($n = 36$) of the respondents say they have no opinion, while 28.8% ($n = 21$) are suspicious, and the remaining 21.9% ($n = 16$) say they trust the information transmitted by the mass media. Therefore, the frequency of seeking information about

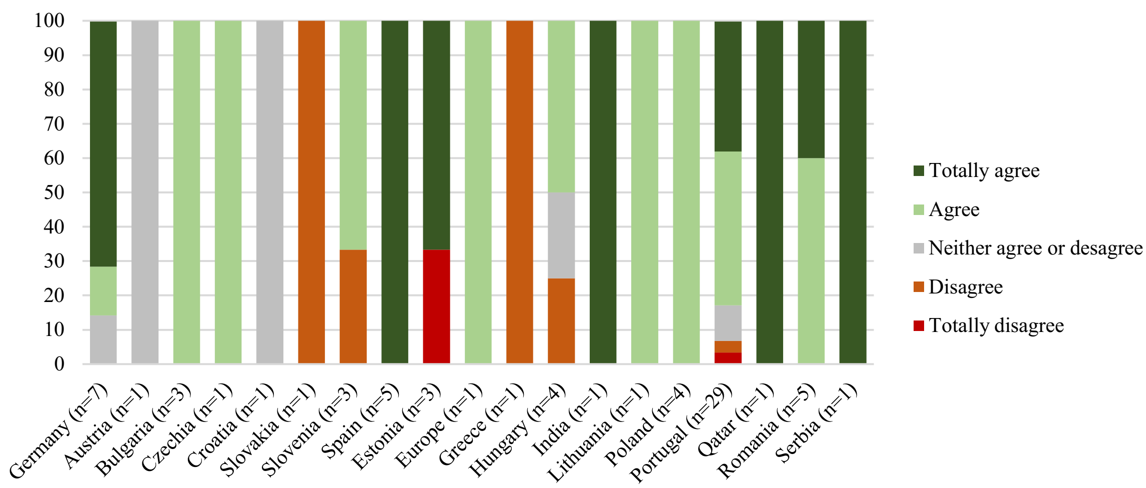

Fig. 6 Degree of support for hydrogen investments in the respondents' country (%, $n = 73$)

hydrogen by respondents can be related to both issues of trust and the regularity of disseminating hydrogen news outside of technical circles. Almost half of the respondents (49.3%, $n = 36$) lack a definite perspective on trusting political decision-makers to implement hydrogen-related decisions, despite acknowledging the interconnectedness of hydrogen and political agendas. On the other hand, there is a high level of confidence in science to solve problems related to emerging technologies.

Subjective stance

Overall, interviewees and respondents expressed positive attitudes towards hydrogen. In this line, ~71% ($n = 52$) of the respondents consider that the use of hydrogen is an environmentally clean option and up to 80% ($n = 59$) support hydrogen investments in their country. Figure 6 illustrates the support of financial investments in hydrogen technologies by stakeholders in their country. Despite overall support, some stances against are expressed mainly by stakeholders from Eastern and Southern Europe.

However, as a critical factor in determining the viability of hydrogen technologies and the hydrogen economy, the source of hydrogen production was emphasized. Interviewees state a preference for hydrogen produced by renewable sources (especially green hydrogen):

> *"We are completely in favor of using hydrogen to fuel consumption where direct electrification is not possible, provided that this hydrogen is a green hydrogen, which means that it is always obtained through water electrolysis, using electricity from renewable sources." (I4).*

In turn, hydrogen produced from non-renewable sources (e.g., gray hydrogen) it is contested:

> *"(...) traditional hydrogen, which is produced from fossil fuels and is practically all the hydrogen that is produced today, and which we want to end (...). We should end it." (I5).*

The use of non-renewable sources for hydrogen production is also contested, even if the technology aims to capture CO_2 emissions and to produce clean or low carbon hydrogen (e.g., blue hydrogen). Interviewees expressed some resistance regarding blue hydrogen since its production is based on natural gas, which means that energy dependence on fossil fuels persists—as well as all the social and environmental related issues.

> *"I think that internationally [blue hydrogen] is not really the vision that has been predominant and what is currently happening within the constraints of energy dependence, namely, the case of natural gas, means that these forms of hydrogen can be disregarded, [--] also because there are large associated investments. It is not really the solution that we are considering". (I1).*

Regarding hydrogen that could be produced from both renewable and non-renewable sources (e.g., turquoise hydrogen), some interviewees share a tendency to accept it. However, it is said that these technologies will be transitionary and used in very specific sectors.

> *"in fact this type [turquoise hydrogen] (...) I think it will eventually have some role in terms of a niche" (I5).*

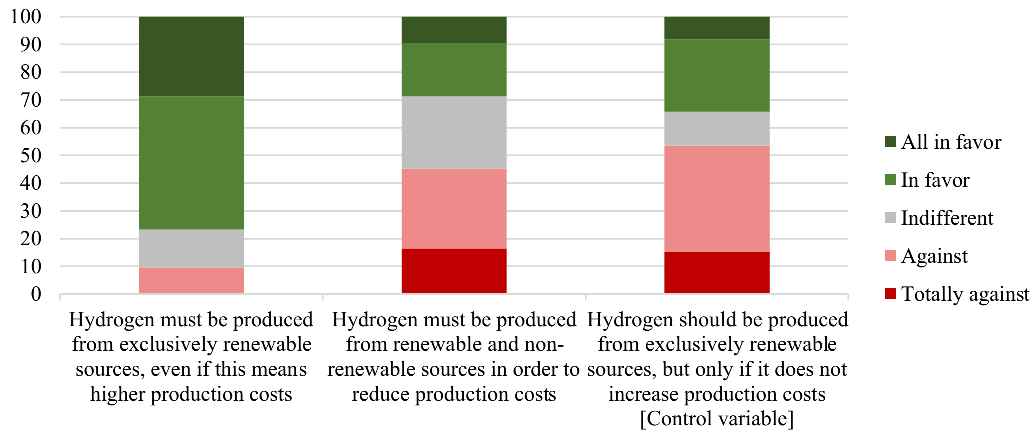

Fig. 7 Respondents subjective stance towards HPSs (%, $n=73$)

Knowing that there might be a positive predisposition towards hydrogen produced from renewable energy sources and a negative predisposition towards hydrogen produced from non-renewable energy sources, we decided to test these predispositions by adding the factor "cost" (see Fig. 7). More than two-thirds (76.7%, $n=56$) of respondents agreed that utilizing renewable energy for hydrogen production is critical, even if it results in higher costs, which suggests high socio-ecological values. Furthermore, 53.4% ($n=39$) of the respondents disagree that "Hydrogen should be produced from exclusively renewable sources, but only if it does not increase production costs", which sustains the previous result.

Regarding the use of non-renewable energy sources for hydrogen production, nearly half of the participants (45.2%, $n=33$) are against it, even when implemented in conjunction with renewable sources and lower production expenses. This supports our prior interpretation of the data, indicating a negative predisposition towards the acceptance of all types of hydrogen that are not produced from renewable sources. However, it should be noted that nearly one in four individuals have a neutral position or are supportive of utilizing non-renewable sources of energy. For these respondents, socioeconomic values may hold greater importance than environmental concerns. The control variable follows the trend of the previously analyzed variables, which strengthens the results.

The effects of relationships

According to Kendall's Tau-b correlation test, there is no correlation between the source of hydrogen production and the subjective stance towards hydrogen (see Table 6). This indicates that the method of hydrogen production might not be a predictive factor in determining attitudes and support for hydrogen. Essentially, this means that the propensity to accept or reject a technology cannot be attributed solely to the technology itself, but that other factors may be involved.

It is essential to examine the connections between the variables analyzed in this study in a comprehensive manner. Figure 8 endeavors to illustrate the intricate nature of these relationships.

The results of the Kendall's Tau-b test show that there is a strong positive correlation between the sustainability orientation of the organizations to which the respondents belong and their familiarity with hydrogen technologies and policies. This may be related to the fact that these organizations promote hydrogen information events, as mentioned by the respondents.

Knowledge, in turn, is positively related to sources of information and respondents' trust in science, policymakers and the media. There is also a strong positive correlation between sources of information and trust. These two are positively related to support for hydrogen investment. In this sense, the results may suggest that the delivery of the message and the messenger are more important than factual knowledge of the issue.

Trust, perceived benefits, attitudes and support are also strongly positively correlated, unlike risks. The latter do not vary in the same way as benefits, which may indicate that they are incompatible technological concepts.

Finally, governance expectations are positively correlated with support. This suggests that support is higher when hydrogen is perceived as an opportunity for energy democracy.

Based on the results of the non-parametric tests (see Additional file 4), No significant group variances were observed with regards to hydrogen positions, suggesting weak correlations between sociodemographic factors and perceptions.

In addition, no significant differences were found among the groups in terms of their stance on hydrogen

Table 6 Kendall's Tau-b correlations between source of hydrogen production, attitudes and support

		(1)	(2)	(3)	(4)	(5)	(6)
"Hydrogen must be produced from exclusively renewable sources, even if this means higher production costs"	*τb*	–					
	p						
	N	73					
"Hydrogen must be produced from renewable and non-renewable sources to reduce production costs"	*τb*	−0.518**	–				
	p	< 0.001					
	N	73	73				
"Hydrogen should be produced from exclusively renewable sources, but only if it does not increase production costs" [Control variable]	*τb*	−0.358**	0.248*	–			
	p	0.001	0.010				
	N	73	73	73			
"I am in favor of investing in hydrogen technologies in my country"	*τb*	0.099	0.142	−0.123	–		
	p	0.336	0.153	0.223			
	N	73	73	73	73		
"The use of hydrogen as an energy source is good for the environment."	*τb*	−0.024	0.186	−0.050	0.548**	–	
	p	0.815	0.059	0.617	< 0.001		
	N	73	73	73	73	73	
"The consequences of using hydrogen are acceptable for future generations"	*τb*	0.030	0.120	−0.038	0.548**	0.793**	–
	p	0.770	0.230	0.706	< 0.001	< 0.001	
	N	73	73	73	73	73	73

**The correlation is significant at the 0.01 level (2 ends)

*The correlation is significant at the 0.05 level (2 ends)

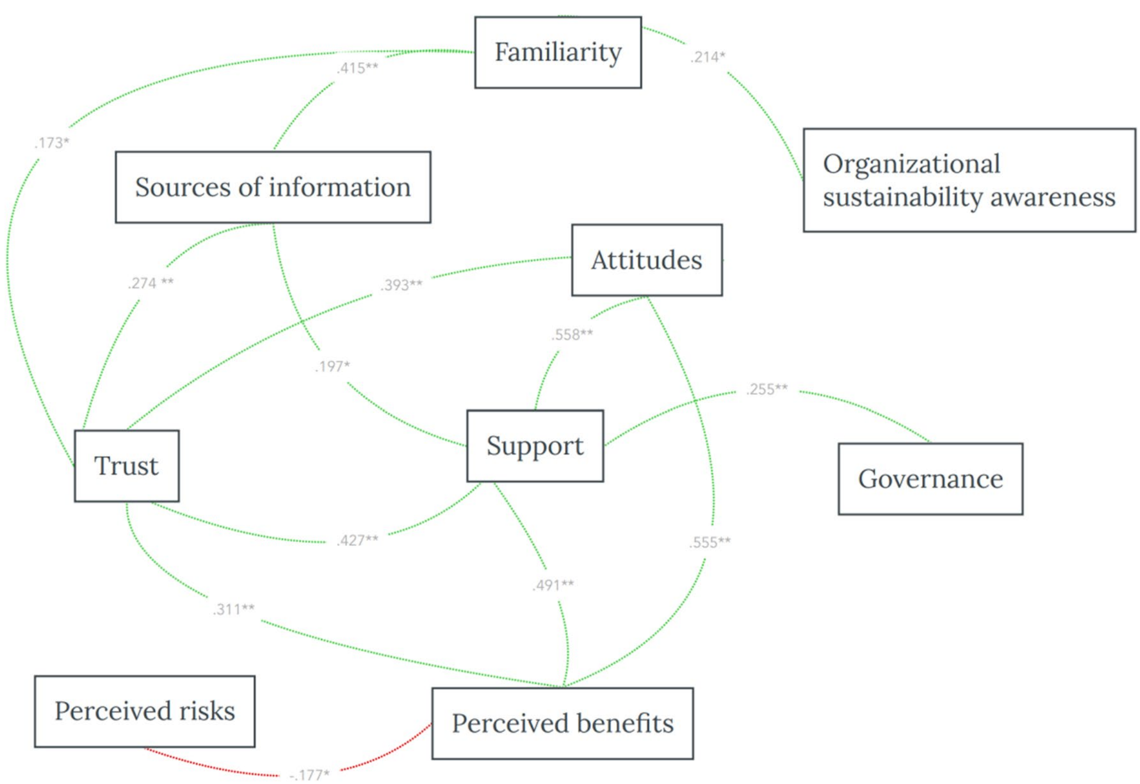

Fig. 8 Relationship between variables

Table 7 Differences among the stakeholder groups using the Kruskal–Wallis nonparametric test

Variables	Test statistic[a]	*p* value (*p*)	Decision[b]
Subjective Stance	24.135	0.002	Reject the null hypothesis
Source of hydrogen production (Renewable)	12.274	0.139	Retain the null hypothesis
Source of hydrogen production (Non-renewable)	10.884	0.208	Retain the null hypothesis

Each row tests the null hypothesis that the Sample 1 and Sample 2 distributions are equal. The asymptotic significances (two-sided test) are displayed. The significance level is at 5%

[a] The test statistic is adjusted for ties

[b] Significance values were adjusted by Bonferroni correction for several tests

production methods (see Table 7). Previous findings (section Subjective stance) suggest that the groups generally favored renewable energy sources for hydrogen production and opposed non-renewable sources.

However, the test results reveal statistically significant differences ($p < 0.01$) in the groups' stances towards hydrogen (see Table 7).

The independent samples nonparametric test revealed significant statistical differences at the 1% level between NGOs and three groups: political sector ($p = < 0.001$); hydrogen consumers ($p = < 0.002$); and non-profit research centers ($p = < 0.007$). In addition, there were significant differences found at a 5% level between the non-profit research centers and the political sector group ($p = < 0.042$). A closer look at the data reveals that individuals affiliated with NGOs have a more critical stance towards hydrogen.

Discussion

The results presented above show some convergences and divergences with the previously presented literature. In this study, we started with the concept of perceptions to understand the predispositions to accept or reject certain HPSs. Perceptions are understood to be the result of social and psychosocial factors, namely: the organizational level, expectations, technological imaginaries, knowledge, and subjective stance in relation to hydrogen and the technologies for its production.

Hydrogen can be generated from renewable or non-renewable sources. According to the data, there is a tendency to accept hydrogen produced from renewable energy sources, in particular green hydrogen, but there is a reluctance to accept it if its production is not based on these energy sources, namely, gray hydrogen. Regarding hydrogen derived from non-renewable sources but classified as low carbon, such as blue or turquoise hydrogen, there is uncertainty and insufficient knowledge among stakeholders, as well as the belief that this is a temporary solution in the transition process. These outcomes are aligned with the observations of Bentsen et al. [53], who found greater receptivity towards hydrogen produced using renewable sources and a tendency to renounce hydrogen created from non-renewable sources. However, these results suggest that the sole source of hydrogen production is not directly linked to attitudes and endorsement of hydrogen.

In terms of socio-demographic features, most of the respondents are men with high educational backgrounds, in their forties, and hailing from countries in southern and eastern Europe. These characteristics did not seem to have a significant role in shaping the perceptions, given that there was no correlation between educational level and age with respect to perceptions. Moreover, there were no discernible differences between perceptions of men and women, and perceptions were consistent across countries. This could be associated with the relatively small and homogeneous nature of our sample. These findings contradict other studies, which suggest that sociodemographic characteristics may predict the formation of perceptions [37, 51, 52, 60]. Future research with more diverse and representative samples would be valuable in determining the reliability of these results.

Contrary to the findings of the Ricci et al. study [23], our data suggests that knowledge is not directly related to an individual's subjective attitude towards hydrogen. Rather, this stance is influenced by their level of trust in institutions and information sources, as pointed out by Molin [38]. The fact that individuals are unfamiliar with turquoise hydrogen technologies does not seem to affect their support for them. However, despite the lack of information on gray hydrogen technologies, respondents expressed skepticism about these technologies, suggesting that familiarity does not directly affect acceptance. These results are in line with the study by Sherry-Brennan et al. [61], who claim that knowledge alone does not influence the acceptance or rejection of hydrogen.

Similarly, the perceived risks of hydrogen do not seem to have a significant impact on perceptions. This is in line with Ricci et al.[23], who contended that public acceptance goes beyond perceptions of risk, also involving trust in institutions, perceptions of the benefits, costs or socio-economic values, or even expectations and aspirations. On the other hand, perceived benefits are strongly associated with attitudes and support for hydrogen, as stated by previous authors [23, 37, 60, 61]. This may be related to greater uncertainty and lack of knowledge about the risks. Therefore, imaginaries surrounding hydrogen primarily emphasizes its benefits rather than its risks, as in [16, 18, 55–59], with these advantages primarily linked to the use of hydrogen generated from renewable energy sources.

As pointed out by Upham et al. [54], these perceptions are constructed through communication processes that place greater emphasis on the benefits. It will be worthwhile to comprehend the narratives surrounding hydrogen, particularly from the perspective of scientists, political decision-makers, the media, and the major players within the energy sector. In addition, the results show that there is a high level of trust in science, which minimizes the perception of risk and makes the benefits outweigh the risks. This trust, in turn, may be related to the academic and/or professional background of the individuals who participated in this study, as they are highly qualified and belong to organizational cultures where they promote debate and behaviors towards the energy transition. Nevertheless, impact assessment studies should consider all types of risks and consequences arising from the hydrogen economy, from its production to its use, and from micro to macro impacts.

In addition to socio-demographic and psycho-social factors, contextual and structural factors are important in shaping perceptions and opinions about hydrogen, as other studies have already stated [37, 54]. It seems important to highlight this finding: no differences were found between groups in terms of attitudes towards hydrogen production sources; however, there are differences between groups in terms of attitudes and support for hydrogen in general. This suggests that there are shared perceptions between groups and that there is a consensus that hydrogen should be produced from renewable sources, even if there is no in-depth knowledge of the issue. In this sense, these perceptions around the production mode may be based on social representations, as suggested by Sherry-Brennan et al. [61], which suggests that stakeholders, despite belonging to different groups, share the same expectations about hydrogen production [54].

Furthermore, stakeholder groups agree on the need for increased public involvement in decisions relating to hydrogen. Nevertheless, the data reveals that hydrogen remains a topic of limited public discussion, which is a trend consistent with studies conducted over 10 years ago [23, 26, 61]. It appears that citizens are not receiving adequate information on the matter, and hydrogen continues to be confined to experts, policy makers and investors and that the energy transition remains a third-party, despite the subject being central to countries' political and economic strategies [8, 11, 15]. As information is critical for participation, the findings suggest that energy democracy might not be given due consideration.

The SCOT approach suggests that the exclusion of certain groups, such as civil society, from the discourse and decision-making process of hydrogen may explain the differing attitudes and levels of support among groups. Consequently, the NGO group's critical stance may be a result of their position on the decision-making axis and may not be a relevant group in the field of hydrogen. It is crucial to consider that there may be disagreements between various groups regarding the interpretation of technologies [40, 42]. It will be important, therefore, to understand what underlies these differences in interpretations between groups. These differences could lead to conflict, as suggested by social constructivists [40–43, 45, 46], which may hinder the development of the hydrogen economy and, to some extent, the acceleration of the energy transition. Therefore, studying group dynamics and power relations in the hydrogen economy in greater depth will be pivotal.

Furthermore, according to Ricci et al. [22], the acceptance of the hydrogen economy could be viewed as subjective and subject to change as it continues to evolve. In this instance, both our quantitative data on acceptance and attitudes towards hydrogen, which support prior research, along with our qualitative data on the uncertainty and ambivalence that participants still experience (particularly concerning the risks of various HPSs), indicate that the hydrogen economy still requires significant progress if it is to advance at its current rate.

This study has limitations that should be acknowledged, but they could also provide opportunities for future research. The small and unrepresentative sample size hinders the statistical data's robustness and its applicability at the territorial level. In addition, while the interviews offer an in-depth analysis of the dimensions, it is crucial to involve stakeholders from other groups and countries, as well as to specify hydrogen production technologies. Third, as greater involvement from civil society in energy system transformations is expected, future studies could explore how the hydrogen agenda is being governed in different countries. In this context, fourth, it is important to consider how citizens may want to get involved in energy transition discussions and the potential role scientists can play. Finally, it is important to examine the central and peripheral elements of HPT representations among technicians and experts, as well as how these representations are shaped and the narratives surrounding hydrogen strategies.

Conclusions

The purpose of this study was to explore stakeholders' perceptions of HPSs through the lens of social constructions of technology. Thus, the aim was to fill a theoretical and empirical gap in the literature on hydrogen technology acceptance, as well as to fill the methodological gap using a mixed method approach based on semi-structured interviews ($n = 7$) and a questionnaire survey ($n = 73$), while most of the other studies used only one of these techniques. This methodology was crucial to understand stakeholders' perceptions in-depth, as the interviews allowed us to gather information that supported the quantitative data and vice versa. Our results allow us to arrive at the following conclusions.

The findings demonstrate that the groups generally approve of hydrogen generated from sustainable origins, namely, green hydrogen. In contrast, they are resistant to hydrogen produced from non-renewable sources, that is, gray and blue hydrogen. Nevertheless, a distinction can be made between the NGO collective and the groups comprising hydrogen consumers, non-profit research centers and political stakeholders. The former, which primarily comprises respondents from NGOs in Southern and Eastern Europe, presents a more critical stance towards hydrogen. This may indicate that hydrogen strategies in these countries are unlikely to take the direction desired by civil society groups, based on investment in technologies to produce hydrogen from renewable sources. The limited involvement of civil society in hydrogen-related decision-making processes, which makes them an insignificant social group within the SCOT framework, may also explain this critical stance. Based on the findings, it can be concluded that hydrogen has remained on the outskirts of public discourse for over a decade. This is contrary to stakeholders' expectations for greater inclusivity and citizen participation in both the energy transition and hydrogen policies.

Therefore, the results suggest that the perceptions of HPSs are not limited to sociodemographic characteristics and psychosocial factors, such as technological imaginaries about benefits and risks, knowledge, and subjective stance. Instead, they imply social representations anchored in systems of shared social values and imaginaries about hydrogen production. These results affirm the importance of HPSs in shaping underlying attitudes towards the hydrogen transition in different national contexts and highlight the relevance of the source of production for acceptance or rejection of HPSs.

Thus, we make the following recommendations: political decisions should be attentive to possible social injustices (at local, regional, national and international levels) and risks that may arise from the hydrogen economy. These policies should also be transparent and encourage public participation in energy and hydrogen issues, since the energy transition to a sustainable future will depend on structural changes and changes in the behavior of social actors. Consideration must also be given to how hydrogen is produced in a given context and the positive and negative, direct and/or indirect, environmental, social and economic impacts of this process.

This study underlines the significance of considering the social aspects that surround technologies, opposing technological determinism. Moreover, it emphasizes the influence of social constructs in the formation of technologies and subsequently the energy system.

Abbreviations

GHGs	Greenhouse gases
HPSs	Hydrogen Production Sources
NGO	Non-governmental organization

Supplementary Information

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Additional file 1. Reliability Analysis.

Additional file 2. Kendall's Tau-b Test.

Additional file 3. Kruskal Wallis test: By group of stakeholders.

Additional file 4. Nonparametric tests.

Additional file 5. Benefits and risks perceived.

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Author contributions
CP supervised and led the research and conducted the main conceptualizations and theoretical approach. In addition, she was responsible for research design. FT carried out empirical work, including data collection and analysis. In addition, she wrote the main manuscript and prepared the figures and tables. JC was responsible for the statistical analysis and the English language revision. All authors reviewed the manuscript.

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Availability of data and materials
The data sets supporting the conclusions of this article are available upon request.

Declarations

Ethics approval and consent to participate
All participants in the interviews signed an informed consent form. Anonymity and freedom to refuse participation in the study was guaranteed to all interviewees and respondents.

Consent for publication
Not applicable.

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

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