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Review

Green Hydrogen and Social Sciences: Issues, Problems, and Future Challenges

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Abstract: The article presents a review of the research on green hydrogen from the social sciences, identifying its main lines of research, its problems, and the relevant challenges due to the benefits and impacts that this energy vector has on energy transitions and climate change. The review analyzes a corpus of 78 articles indexed in the Web of Science (WoS) and SCOPUS, published between 1997 and 2022. The review identified three research areas related to green hydrogen and the challenges for the social sciences in the future: (a) risks, socio-environmental impacts, and public perception; (b) public policies and regulation and (c) social acceptance and willingness to use associated technologies. Our results show that Europe and Asia lead the research on green hydrogen from the social sciences. Also, most of the works focus on the area of public policy and regulation and social acceptance. Instead, the field of social perception of risk is much less developed. We found that little research from the social sciences has focused on assessments of the social and environmental impacts of hydrogen on local communities and indigenous groups, as well as the participation of local authorities in rural locations. Likewise, there are few integrated studies (technical and social) that would allow a better assessment of hydrogen and cleaner energy transitions. Finally, the lack of familiarity with this technology in many cases constitutes a limitation when evaluating its acceptance.

Keywords: risks; social acceptance; public policies; regulation; public perception; green hydrogen; hydrogen energy; energy transition; renewable energy

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1. Introduction

Clean fuels are key to tackling climate change. Social science research on renewable energy and energy transition has been extensive during the last 40 years and 10 years respectively [1,2]. However, green hydrogen has had less development, even though in recent times it has experienced a strong boost, presenting itself as one of the most viable energy alternatives [3–5]. Therefore, this article aims to review the social science literature on green hydrogen and identify the main lines of research, its problems, challenges, benefits, and possible impacts.

In the current climate crisis, most countries have committed to sustainable models, progressively replacing an energy matrix based on non-renewable energies with an environmentally friendly one [6,7]. In this transit, wind, photovoltaic and green hydrogen energy projects have been implemented. However, these energy projects are not free from causing risks and impacts for society and the environment [8–11], as well as local problems that affect their social acceptance [12,13].

Studies on green hydrogen have focused on investigating technical and economic aspects. Yet, research on renewable energies has identified some variables that could be considered in green hydrogen projects. On the one hand, the social impacts on the landscape, on the value of properties, on economic activities, on health and well-being. On the other, distrust of promoter companies or unfair and inequitable distribution processes for communities and territories [14,15].

In recent years, different international agreements, and Conference of the Parties (COP) have tried to stop climate change. In this regard, the Paris Agreement is especially relevant. For example, Europe aims to be the first decarbonized continent by 2050, according to the Green Deal. To this end, the main areas of intervention are those sectors and activities that produce the most harmful effects on the planet: the energy system, industry, and transport [16].

In this context, green hydrogen has now gained importance as a viable energy alternative. This prominence is due, to a great extent, to the significant increase in the production of renewable energies, the improvements in the technologies for its implementation and its application in industry, heating, and transport. Thus, while some questions about green hydrogen, such as climate balance, have been overcome, issues such as low conversion efficiency remain critical to the development of the technology [17–19]. As a result, in recent years, policies and strategies have been put in place for its implementation. Together with this, a market appeared for investment, innovation, and technological advances in this energy [20].

Despite the benefits of green hydrogen as an alternative to the current crisis, its implementation presents challenges associated with sustainable production techniques and social and environmental impacts. In this framework, the social sciences, through critical observation of the benefits, impacts and risks, can contribute to an effective transition and to reduce the impacts on society and the environment [21,22]. Although scientific production on renewable energy is extensive, research from the social sciences on green hydrogen is only beginning to advance [4,23].

Therefore, what issues and problems have the social sciences research revealed on green hydrogen? From which frameworks have these been worked? And what gaps and future challenges have researchers found?

This review of the literature seeks to account for the current state of research from the social sciences. It is structured in four sections. The first exposes the purpose of the article, the problem, the conceptual contextualization, and the great themes that relate green hydrogen to the social sciences. In the Section 2, we present the methodology used for the selection of the sample and review of the articles, to identify and characterize the lines of research and their problems in the third. Finally, we offer future challenges in the field of study.

2. Materials and Methods

The search for this review was accomplished in SCOPUS and Web of Science (WoS), as they have the widest coverage of current and relevant publications [24]. For the choice of search terms, a preliminary exploration of the results was performed by searching for "green hydrogen" in the social sciences areas of WoS and SCOPUS. Subsequently, a qualitative analysis process of the keywords associated with this set of publications was carried out, which allowed the identification of the most frequent terms with the highest semantic density in this field of study.

In this way, the following concepts were selected to describe green hydrogen as a technology: "clean hydrogen", "green hydrogen", "green fuel", "hydrogenation", "hydrogen production", "hydrogen energy", "hydrogen fuel cell". For the research content, the following terms were chosen: "social practices", "energy justice", "risk perception", "social risk assessment", "social risk", "risk assessment", "qualitative", "socio-technical", "social impact", "opinion*", "attitude*", "acceptance", "governance", "regulation", "sociology *", "vulnerability", "social innovation", "energy transition", "policy", "place attachment", "emotion", "imaginary", "social representation", "citizen", "stakeholder".

As can be seen in Figure 1, the search command was built by combining both sets of terms, using the Boolean operator OR to separate the concepts within the same group, and AND to combine both sets. In WoS, the search was limited to publications included in the Social Sciences Citation Index (SSCI), while for SCOPUS only the six thematic areas associated with the social sciences were considered. Only articles and reviews were examined. Regarding the time frame, no cut-off points were established, due to the novelty of the field and the lack of clear antecedents about the beginning of research on green hydrogen from the social sciences.

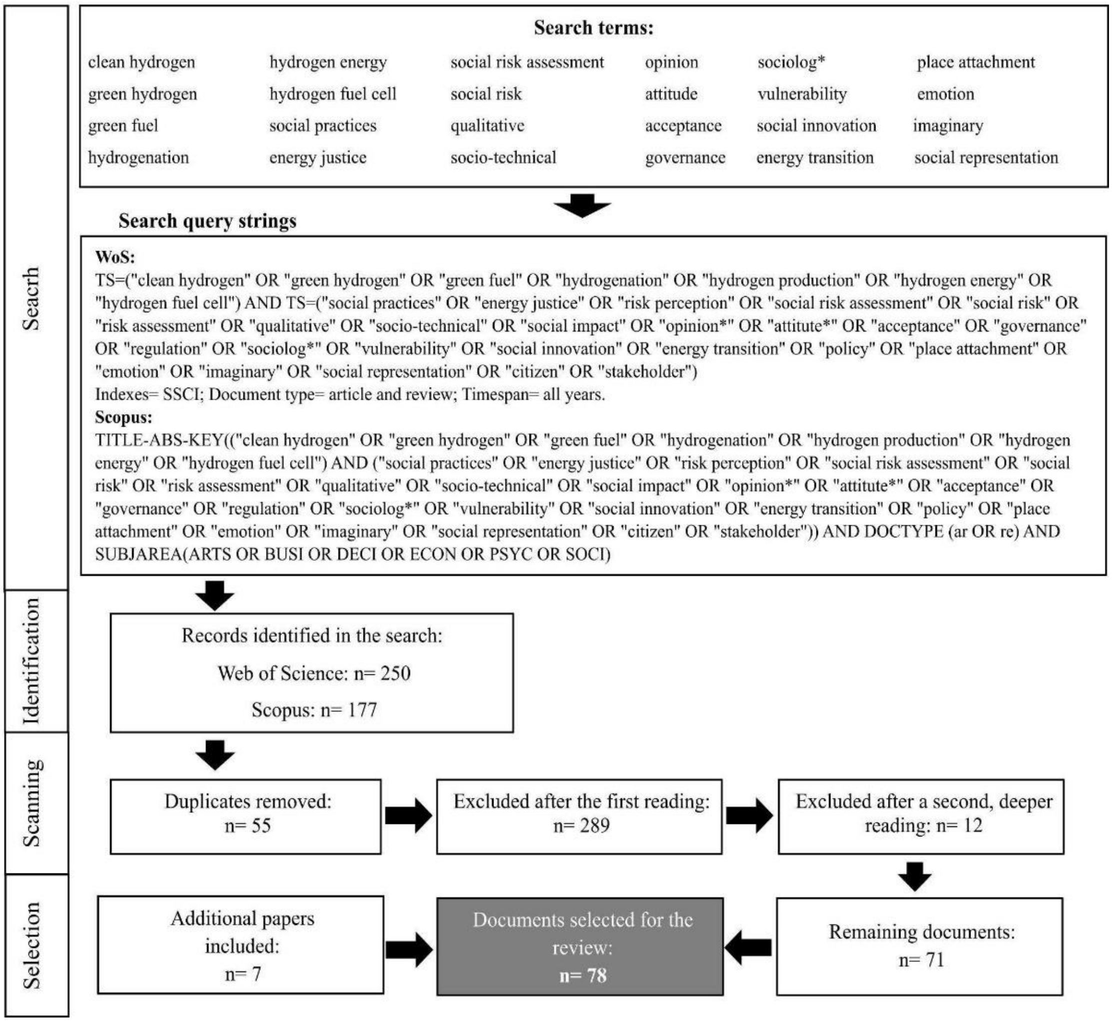

Figure 1. Diagram of the search and sampling strategy. The asterisk (*) is inserted inside the keywords to substitute various possible endings in the search.

The search returned 427 records. After purging the database, 55 documents were identified in both bases, so the first scrutiny phase was carried out with a total of 372 publications. In this first review stage, those publications that met any of the following exclusion criteria were discarded: (1) be written in a language other than English or Spanish, (2) not be articles or reviews, or (3) focus on a research topic that did not correspond to an approach to green hydrogen from the social sciences. A set of 83 documents was selected after this first analysis.

In the second stage of review, a more detailed reading of these 83 documents was implemented, considering the same exclusion criteria indicated above. In this procedure, twelve publications were left out, leaving 71 papers selected. Additionally, four publications have been included in the review that are part of the works cited by publications previously selected to make up the corpus, and three more papers were added to the corpus due to their relevance. Consequently, this review has been carried out based on a total of 78 documents.

Finally, an in-depth analysis of the selected publications was developed, which revealed three areas of research around green hydrogen: (1) risk perception, socio-environmental impacts, and public perception (2); public policies and regulation; (3) and social acceptance.

3. Results

3.1. Descriptive Analysis

78 articles published between 1997 and 2022 were identified. A first increase in publications was observed in 2016 and a second, much more pronounced, since 2020 (Figure 2). Most of the works, as shown in Figure 3, focus on the area of public policy and regulation (37 publications) and social acceptance (28 publications). Much less developed is the field of social perception of risk (13 publications).

Figure 2. (**A**) Temporal evolution of the frequency of publications per year, according to the research topics; (**B**) Total number of publications by theme.

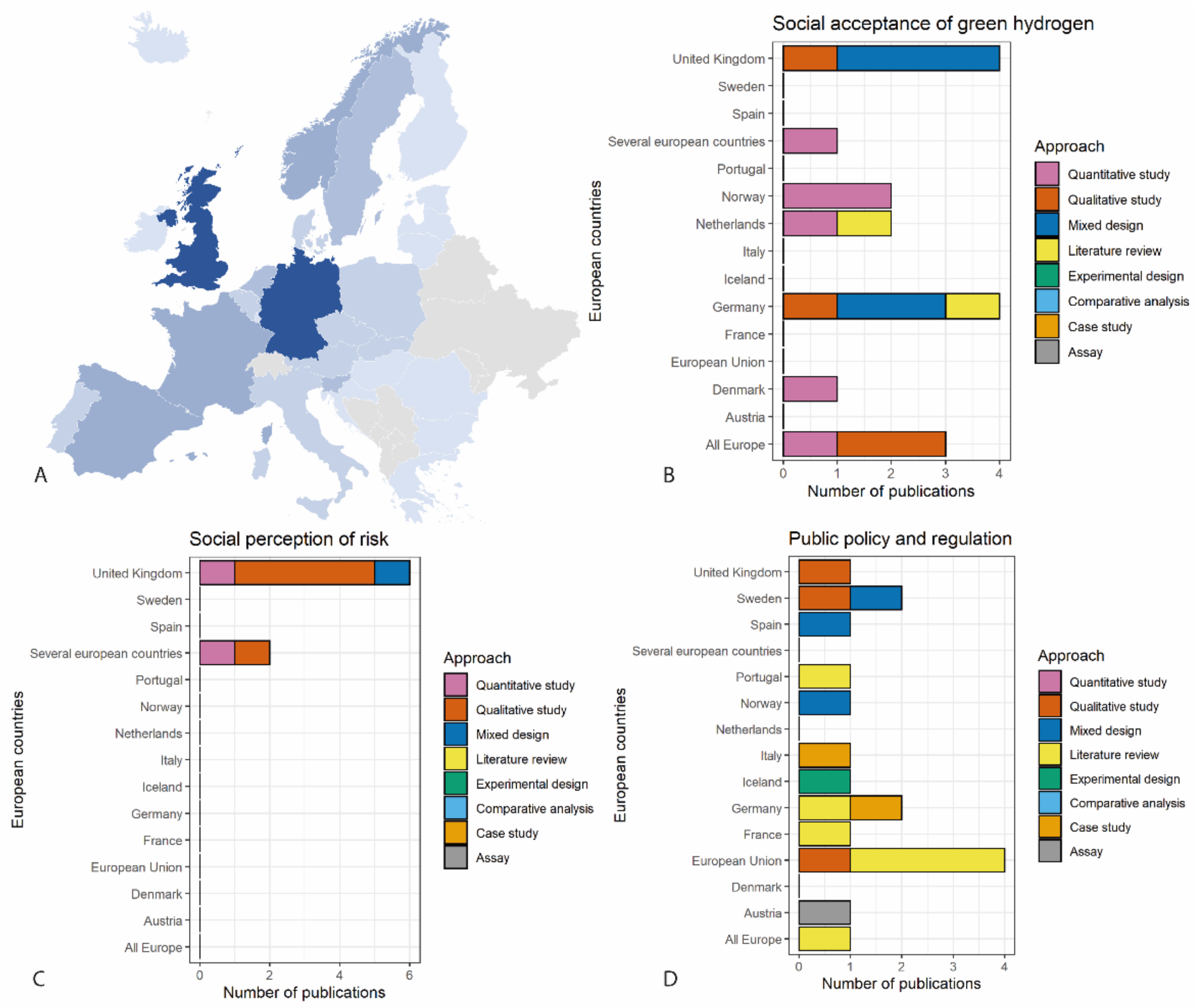

Figure 3. Predominance of themes and the methodological approaches used in Europe. (**A**) the greater intensity of the blue color indicates the countries with more frequency of publications; (**B**–**D**): frequency of methodological approaches for each of the topics addressed.

Regarding the geographical distribution of research, Europe leads the studies, followed by Asia. No papers located in South America were found in the review. In Europe (Figure 3), publications on social acceptance predominate, followed by public policies and regulation. These investigations are led by Germany and the United Kingdom, with mixed design outweighing as a methodological approach.

In Asia (Figure 4), Japan and South Korea are the countries that lead the publications related to the social acceptance of green hydrogen. The quantitative approach is the most frequent to address the different topics analyzed.

The United States stands out for having research that addresses the three topics analyzed here (Figure 5). In public policies and regulation, literature reviews predominate as a methodological approach. This is seen in research conducted in Europe, Asia, and Africa, as well as in research conducted on a global scale or in studies that do not specify a particular region (Figure 6).

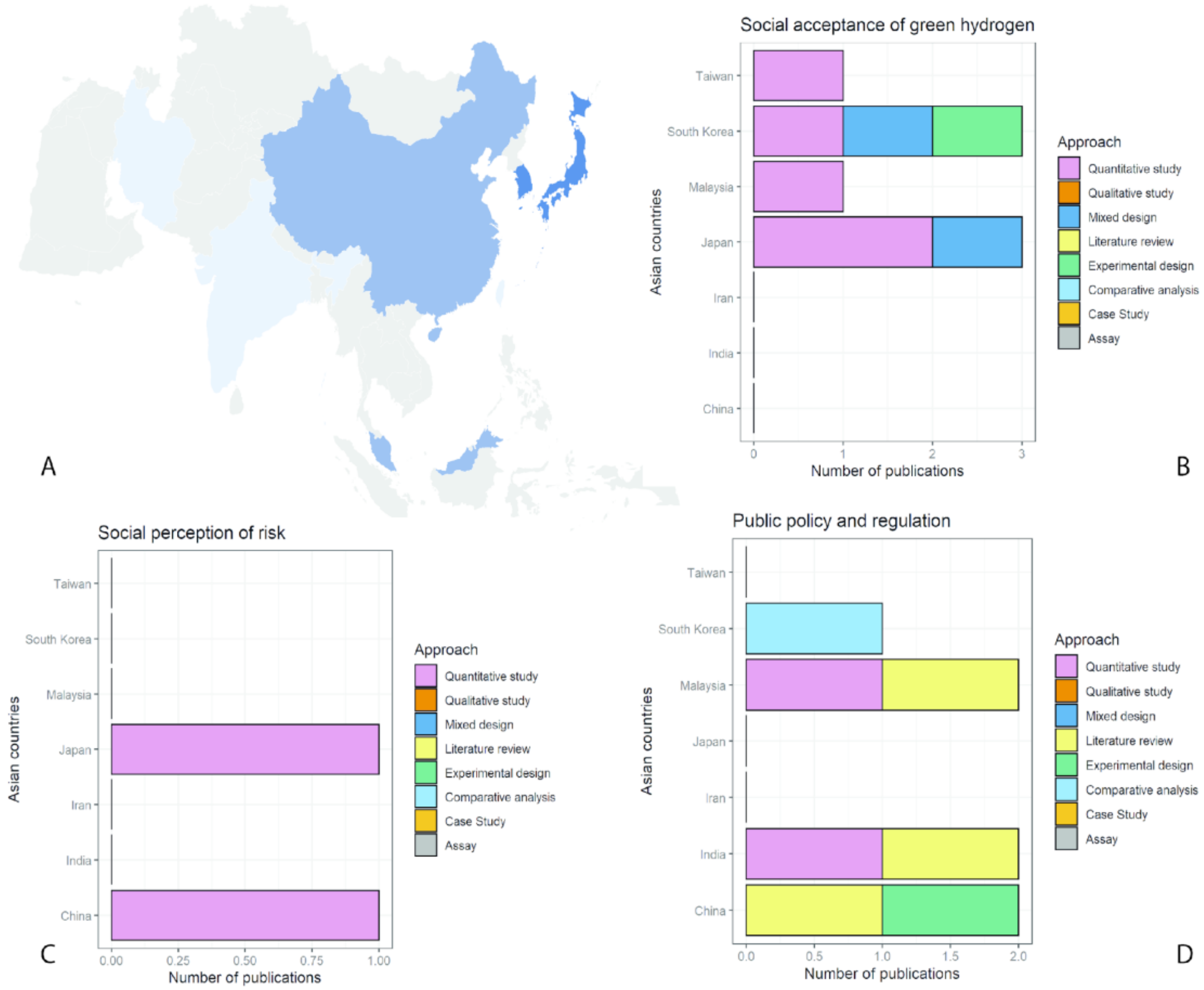

Figure 4. Predominance of themes and the methodological approaches used in Asia. (**A**) the greater intensity of the blue color indicates the countries with more frequency of publications; (**B**–**D**): frequency of methodological approaches for each of the topics addressed.

Regarding the research groups, Figure 7 shows 37 groups made up of at least three researchers. Among these, seven groups stand out: (1) Bellaby, Flynn and Ricci; (2) Dutschke, Oltra, Sala, Upham, Schneider, Klapper, Lords, Bogel, Burghard, and Brinkmann; (3) Bayer, Langhelle, Thesen and Tarigan; and those linked by (4) Bauer, (5) Whitehouse, (6) Park, and (7) Al-Amin.

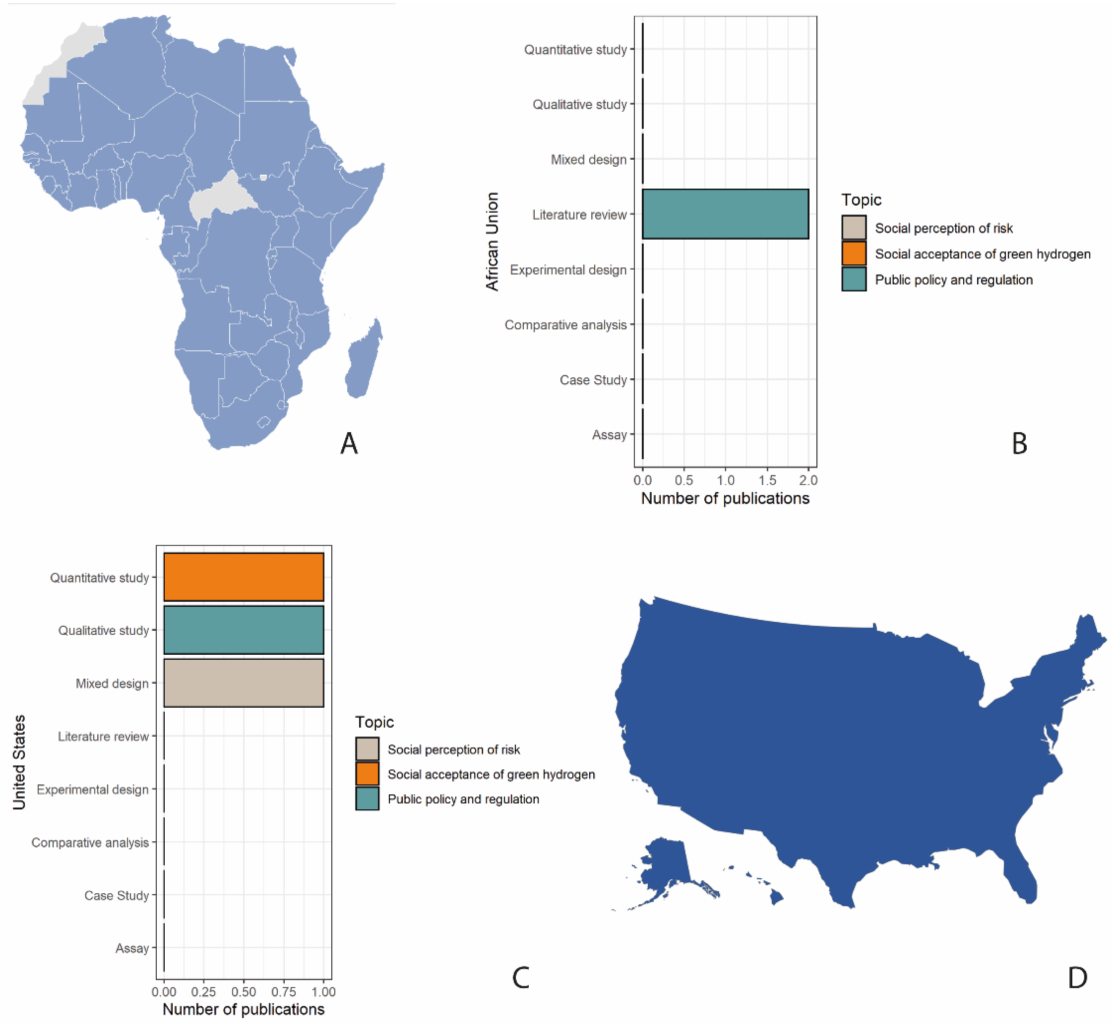

Figure 5. Predominance of themes and the methodological approaches used in North America and Africa. (**A**) the greater intensity of the blue color indicates the countries with more frequency of publications; (**B**–**D**): frequency of methodological approaches for each of the topics addressed.

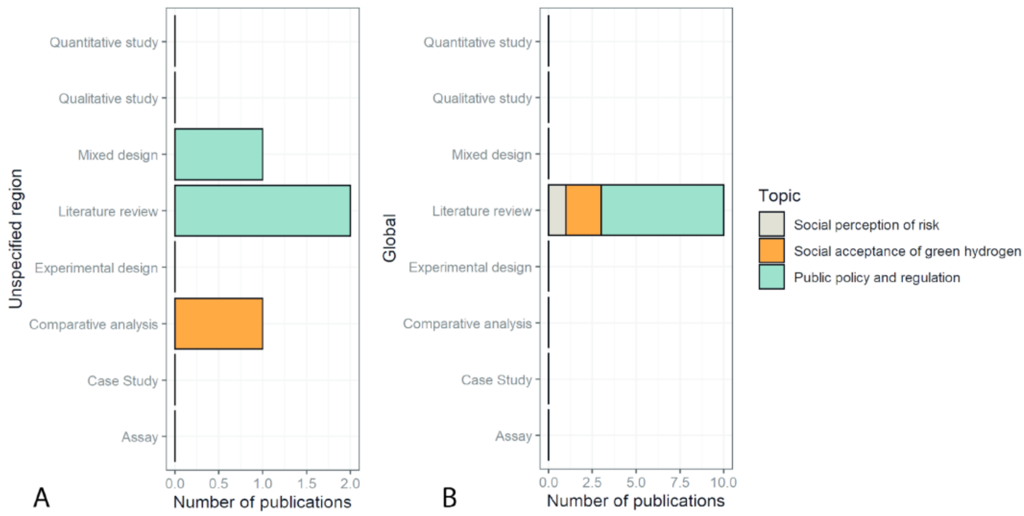

Figure 6. (**A**) Frequency of the methodological approaches used in the different topics analyzed in research that does not specify a region; (**B**) Frequency of methodological approaches in the different topics analyzed on a global scale.

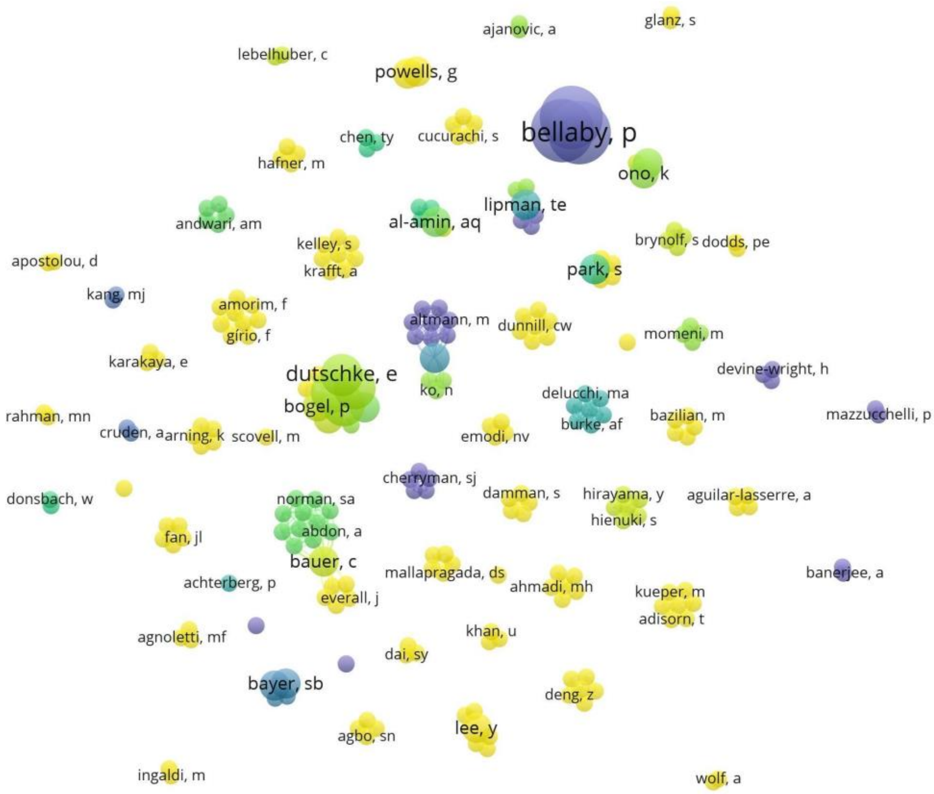

Figure 7. Network of authors.

3.2. General Findings

To understand the development of research on green hydrogen, we resort to the value chain as a key element that describes the process from its production to its final use in different applications. Hence, it is crucial to realize that the different stages of the value chain have distinct impacts on people's lives, depending on the local context in which they develop and the processes by which they are introduced [25].

In this sense, the green hydrogen value chain begins with the selection of a renewable source for its production, since both processes are closely interconnected [26], and therefore constitutes a key aspect to understand the social acceptance of green hydrogen. In fact, in terms of consumer preferences, renewable energy sources are the most desirable for hydrogen production [27]. However, little research from the social sciences has focused on green hydrogen production, and research related on the possible environmental impacts of these renewable sources for hydrogen production is poorly developed in the literature, despite the relevance it has in its acceptance. In this particular topic, Delpierre et al. [5] analyzed the environmental impacts of green hydrogen production, and although they do not make an evaluation of the social dimension of these impacts, they do highlight the need for their approach in future research.

One of the peculiarities of hydrogen is its potential to store energy, which can later be released as demanded. However, the present review did not find research within the social sciences that addressed this stage of the green hydrogen value chain (storage and transport), so this topic is not further developed, beyond the concerns for the safety of this technology that are greater in the storage and transport stages [28].

On the other hand, research addressing the end use of green hydrogen has made a more comprehensive development of the social dimension, including domestic applications and use in both private and public transport. Of these applications, the use of green hydrogen in the transport sector is the area most developed by social science research. At this stage of the value chain (end use) research highlights the importance of the end user in the success of energy systems [29]. It also highlights how the different applications or uses of green hydrogen are little known by the population in the context of energy production [30].

3.3. Risks, Socio-Environmental Impacts, and Public Perception

The literature around the risks and potential impacts of green hydrogen highlights issues such as attitudes, reactions, and opinions [28,31–33], knowledge [34–36] and risk perceptions and expectations [23,37–39].

In the first decade of the 21st century, general views and attitudes towards hydrogen were rather neutral or evasive and not shaped by an altruistic concern for a greater public good [33]. Currently, the public perception of green hydrogen, particularly in countries such as those in Eastern Europe, where hydrogen energy is underused and has poor infrastructure, denotes a lack of knowledge of the production processes as well as the benefits that this would bring [31]. In other words, a certain uncertainty and concern appears among citizens. Likewise, a low public awareness is evident in other contexts, with non-hostile or negative opinions. Citizens also demand more information about the advantages and benefits of the transition to this energy source [28].

This evidence is in line with Ono et al. [40], who identified that by providing information on the risks associated with green hydrogen applications (such as hydrogen refueling stations), their acceptance is increased by alleviating feelings of fear or uncertainty. This highlights the importance of communication in reducing concerns associated with this technology. Therefore, it follows that when people have a higher level of knowledge, the opinions would be more positive. This is also supported by studies on hydrogen fuel cells, where safety perceptions would favor their use [32].

However, studies show that the degree of knowledge about green hydrogen in the population is precarious [31]. Therefore, the need emerges to involve different actors and systems to generate shared or co-constructed knowledge in pursuit of future energy policies, where scientific knowledge and lay knowledge can interact and cooperate [35].

Given the low probability that an actor or system can guide and build valid knowledge and solutions on the energy problem on its own, the inclusion and participation of the public becomes essential. This will allow building a perception of security of green hydrogen, generate confidence in its associated technologies and, consequently, promote governance that helps reduce opposition to this type of energy in favor of the transition [34,36].

In terms of green hydrogen safety (Figure 8), research from the social sciences has focused mainly on understanding how the safety of this technology is perceived by people, knowing that it has been commonly seen by the public as a highly explosive substance [41]. In the literature, safety does not appear as a determining variable in the acceptance of green hydrogen, particularly when factors such as familiarity, knowledge and trust towards the technology are involved. However, this perception of safety would also be determined by the type of application. For example, hydrogen refueling stations are perceived as more dangerous than vehicles when compared to gasoline stations and vehicles respectively [32]. In fact, the biggest safety concerns focus on the storage and transport of green hydrogen, rather than its end-use in the transport sector [28]. In terms of hydrogen storage, safety issues are completely overlooked, according to Sgarbossa et al. [26].

In this sense, concerns about the safety of hydrogen have a high correlation with trust, which goes beyond communication strategies about this energy source. Such is the case in Taiwan, where trust in the local industry and its ability to follow safety standards minimize concerns in this area and therefore have little effect on its general acceptance [42]. In contrast, in the Netherlands, low confidence in science and technology in general has promoted a marked decline in the acceptance of hydrogen between 2008 and 2013 [43].

Consequently, we can reveal the perception of risks on the safety of technologies associated with green hydrogen, mainly related to storage sites, transportation, and use of pipelines. In this area, trust, the availability of technology and the legitimacy of its implementation are important.

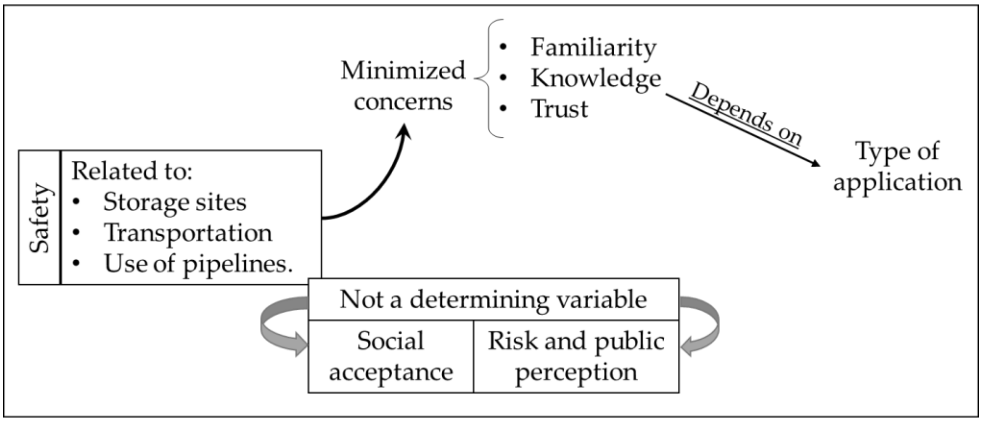

Figure 8. Factors related to the safety of green hydrogen.

Therefore, the perceptions about green hydrogen show a high approval at the general level [41]. However, the literature points to concerns related to some ecological and social impacts. Emodi et al. [23] state that the perceptions and factors related to the risks and impacts that would affect the acceptance of technologies associated with green hydrogen would be associated with the initial understanding, the demographic effects, the security of the energy supply and its regulations and standards, economic costs and benefits, policies, environmental awareness, ways of production, storage, application issues, location and proximity, and trust and communication.

Finally, even though people have been gaining knowledge over time regarding green hydrogen, there is no change in the perception of its risks or benefits [39]. In this sense, concerns prevail about on the one hand, its costs, impacts on the environment and efficiency and, on the other, safety appears as an important variable, but not a determining one, since it is assumed as given from the beginning of the projects [28]. These various concerns of stakeholders need to be addressed in future research due to its impact in planning task associated to green hydrogen development [26].

3.4. Public Policies and Regulation

The literature in this area shows interest in two aspects: (1) the energy transition and infrastructure deployment, and (2) the design of policies for decarbonization.

In terms of transition and infrastructure, the research evaluates the potential of certain geographical regions, countries, and territories with developed economies to carry out these energy transition processes. For example, case studies on Norway [44], Iceland [45], Austria [46], Italy [47], Spain [48] and the European Union [49]. These analyzes identify the technical and economic possibilities to implement the transitions, the viability to deploy a hydrogen economy, and the specific, current, and potential conditions of future markets that allow building sustainable energy systems [50]. For example, land and sea transport systems [51–53].

Another key aspect is the studies of specific technologies developed in relation to hydrogen in certain countries. Research shows interest in analyzing technologies to produce and store hydrogen and deliver it to end users [16,54–56]. Regarding production and storage, several analyzes focus on the capabilities and difficulties of developing countries to deploy hydrogen technologies [57], such as Iran [58], India [59] and Malaysia [17], which are internationally recognized as powers in the field.

About policy design, the literature shows that the relationship between policies and economics is intrinsic, given the interest in analyzing how hydrogen can help decarbonize industrial processes [18,19], the emphasis placed on the effect that transition strategies and regulatory frameworks can have over the consolidation of hydrogen economies [46,47], and the investment in this kind of energy [48]. The policy requires strengthening the substitution of fossil fuels for renewable energy systems [60]. Insufficiencies in the designs devoted to this work are highlighted [61], but also encouraging prospects in countries that, although they have large sources of renewable energy, such as African countries, suffer from technological deficiencies that affect the deployment of this type of energy sources [20].

At this point, the research highlights the relevance of the analysis of the regulatory frameworks that could promote or discourage the development of the green hydrogen industry. Thus, some works have focused on studying the characteristics of the legislation and institutions of certain transnational regions—both in terms of renewable energy and green hydrogen—mainly the European Union [62,63]. Other studies have pointed to the ability of communities to carry out endogenous regulatory processes. For example, analyzing the forms of community governance in the production of energy such as wind power and green hydrogen [64], or community energy storage [65]. This shows the importance that factors that affect the deployment of community adoption processes of this type of emerging energy have in the broader chain of hydrogen and renewable energies [66]. Social elements are found in the literature that are not always highlighted in the analyzes developed in the area.

To identify regulatory and legislative conditions for hydrogen use, scenario analysis is useful. In this regard, the literature studies the stage at which its use is at a broader level of climate policies and legislative frameworks of the European Union [63,67], as well as more applied aspects, such as Europe's strategic plans for hydrogen [49]. These studies are interested in the real possibilities of introducing hydrogen into renewable energy systems, beyond the discursive dispositions that exist on the need to maintain sustained decarbonization processes of energy matrices.

In green hydrogen, the socioeconomic and sociopolitical contexts in which regulatory policies are developed influence people's attitudes toward their technologies [38]. There is an important difference by country, and the published evidence echoes this [16,54–56]. In countries with high levels of official support for hydrogen technologies, whether at the production, storage, or consumption stages, higher levels of public acceptance are noted. In these countries, it is conceivable that these levels of acceptance and expansion of the green hydrogen society involve a set of factors that have been little studied.

Therefore, it is possible to recognize that this expansion of the green hydrogen application frameworks end up being guided by ideological or cultural issues, such as gender or education [30,68], and not only by technological aspects widely studied by the literature. The arrangement of legislative and regulatory frameworks developed by nations is so complex that it is possible to visualize (even) opposing positions within the same transnational space (such as the European Union), regarding the paths to be followed by countries to develop the use and massification of this fuel [63,67]. This would be slowing down the substantial progress towards a general hydrogen society [61], having as one of its most notable consequences the different public policy emphases that each country attributes to green hydrogen in society, some of which may favor the successful energy transition and others not, becoming obstacles to this task. Aspects such as communication [69] and education [70,71] appear, as in the case of Japan and Southeast Asian countries, where it has been concluded that providing information on the risks associated with green hydrogen applications (such as hydrogen refueling stations for vehicles), increases its acceptance by alleviating feelings of fear or uncertainty associated with this technology [39,40,72].

In Europe, on the other hand, the literature studied analyzes the status of the use of this element in a broader framework of climate policies and legislative agendas [63,67], as well as applied aspects of these policies, such as strategic plans for hydrogen [49]. It is worth noting the attention of these studies to analyze the real possibilities of introducing hydrogen into renewable energy systems, beyond the discursive provisions that exist on its importance for the processes of decarbonization of energy matrices [57]. It is interesting that the same development that has taken place in the European Union has often led to contradictory positions among the same countries regarding how to carry forward these processes—strongly based on the field of economy and industrial development-, unlike what has been said about the Asian countries, which emphasize the use, perception and social acceptance of hydrogen technologies [17,42,73,74]. This shows that national contexts determine to a large extent how green hydrogen development processes are worked out at the policy level, whether in the technological production phase or in the social amplification of its use to the wider society.

Consequently, the publications show the interest in analyzing the condition of the markets to launch decarbonization industries, including hydrogen. Also, the technical challenges presented by these industries [70,75]. In this, it is important to direct attention to the analysis of supply and demand [18,58], with a view to consolidating zero-emission policies in the medium and long term. This type of analysis is complementary to that of the social costs and benefits of hydrogen, which are relevant to identify the possible technical applications that are being implemented in specific areas of the daily life of populations, such as fuel cell vehicles [76] and passenger transport [52].

3.5. Social Acceptance and Willingness to Use Associated Technologies

The social acceptance of green hydrogen plays a fundamental role in the adoption of its applications, both at the residential and transport levels. In general, green hydrogen and its associated technologies such as fuel cells and their small-scale applications in the residential or transport sector are little known by the population in the context of energy production [30]. These studies have been executed in advanced countries, emphasizing the promotion and social benefits of hydrogen fuel cell vehicles [70,76–78] and hydrogen service stations [72,79]. That is, surveying sociotechnological factors that affect their social acceptance [80].

Access to more information would tend to positively modify the disposition towards this energy source [68,69,81]. The role of communication in the social acceptance of green hydrogen is essential, as it can promote trust in this technology [82]. In this sense, dissemination and education emerge as important aspects to strengthen the communication and acceptance of green hydrogen [70,71,83,84]. They are key tools for promoting best practices in the industry and reducing the potential environmental and social impact that this type of technology can generate in the long term [5,85].

However, according to the available evidence, people's position on green hydrogen and their willingness to use associated technologies are influenced by elements such as the existence of energy transition policies in the country of residence, sociodemographic factors [86], psychological [87], cost [88,89], technical aspects, mainly associated with the installed infrastructure, direct use or familiarity with the technology [90,91], factors related to the risks associated with these technologies [27,40] and trust in the industry [42] as well as in science and technology in general [43].

In countries with policies supporting hydrogen as a new energy source, greater awareness and acceptance of this technology has been found [87]. The local context in which the technology is developed, as well as the type of applications that are implemented, are dimensions that influence its acceptance [25]. However, support for green hydrogen may be more associated with individual characteristics such as gender, education, previous attitude, among others, which should be studied for a better understanding of their acceptance [30,69].

In terms of costs, most of the research has focused on the transportation sector, specifically on private vehicles. The results suggest that although cost is a key aspect [88,89], people would be willing to pay more for emission-free fuels [74,89], especially if they can compete with conventional vehicles in terms of performance [74]. For many potential consumers, the environmental benefits that can be generated by the development of a green hydrogen market become one of the elements that lead to the acceptance of the technology [81]. Therefore, environmental awareness has a clear influence on the intention to purchase and use green hydrogen and its associated technologies [81,92].

Nevertheless, little has been studied about the acceptance of green hydrogen and its application in public transport. Only one investigation was found on the willingness to pay, which indicates that it is higher to support the large-scale introduction of hydrogen buses for their environmental benefits. Environmental concern appears once again as a key variable [93], so providing technical information on the potential environmental impacts of technologies favors the acceptance of green hydrogen [94].

Different investigations have found that familiarity with technology is key [85], since having direct driving experience with fuel cell vehicles, either as part of a driving test experiment [91] or the direct experience of private owners of this type of vehicle [90], people show a high acceptance of this type of technology. In these cases, concerns such as the safety of hydrogen as a fuel are minimized. These experiences increase knowledge of the technology and promote pro-environmental attitudes among people, which favors the acceptance of green hydrogen and its applications [68].

However, it is necessary to point out that this acceptance may vary if the application of hydrogen is aimed at residential use (heating or cooking), since this type of application intervenes with social practices, especially use in the kitchen. Using a virtually invisible flame disrupts sensory-mediated practices, calling for actions to address this perceived interference and perhaps adapt the technology [95].

On the other hand, the transformation from the high acceptance of green hydrogen as a technology towards a willingness to buy is mainly conditioned by the available refueling infrastructure [90,91]. Therefore, in the transportation sector, hydrogen fueling stations are considered a critical factor for the growth of the fuel cell vehicle market and industry [40,74]. Increasing the number of hydrogen refueling stations, as well as their capacity, and improving the efficiency of fuel cell electric vehicles are problems on which it has been suggested to work to increase the acceptance of their application in the transport sector [74]. But, understanding the acceptance around the different applications is essential to respond to market demands, which go beyond the transport sector, with significant growth in the industrial sector [96].

This knowledge supports the need to understand the end users of these technologies and their characteristics, as well as their incorporation into design processes from an early stage [29]. This improves communication processes [68] and, together with education, constitutes key aspects in the acceptance of hydrogen and its uses [71,83].

4. Conclusions and Challenges for the Social Sciences

Research on green hydrogen presents the following challenges regarding risks, socio-environmental impacts, and public perception. The first is the lack of studies on evaluations of the social and environmental impacts of hydrogen on local communities and indigenous groups, as well as the participation of local authorities in rural locations [23]. Although some authors analyze the environmental impacts of green hydrogen production [23], the social dimension of the evaluation is non-existent. This also generates the need to incorporate economic and political variables [85].

The second, highly correlated with the first, are studies that are not only technical or social, but rather integrated, where projects can be linked to people, their histories, economies, and cultural variables of local contexts. This would allow a better assessment of hydrogen and cleaner energy transitions [97]. The third is related to water consumption (and its social impact) required by hydrogen through electrolyzers, as well as distributive justice. The latter can be exemplified in topics such as energy independence, the creation of local jobs and environmental responsibilities [5]. Finally, Emodi et al. [23] emphasize the need for studies on the social perception of hydrogen use, which would be vital for the knowledge, acceptance, governance, regulation, and relevant policies of green hydrogen.

Research on public policy and regulation of green hydrogen presents challenges in (a) infrastructure regulatory solutions, (b) improved technical analyzes on hydrogen and other e-fuels, (c) analyzes on socio-technical systems, (d) case studies on technologies available and (e) studies on the governance of renewable energy systems. Regulatory solutions refer to accounting for barriers to device deployment [56], such as service stations [72,79] and vehicle trade [51]. These challenges point to improving multi-criteria analyses, the Hydrogen Industry Development Levels Index [55] and the sustainable value approach extended to the study of more hydrogen production centers [54]. This can improve decision-making [49], the sensitivity of uncertainties about decarbonization [62], the preferences of stakeholders in e-fuels [53] and the imitation of the reciprocal competitive response of companies [50].

Analyzes of sociotechnical factors require more research given their still limited coverage in terms of applicability [19]. This reinforces the strengthening of the quantitative modeling of scenarios for sociotechnical prospecting [44], the development of internationally agreed measurable indicators [75] and the expansion of sociotechnical experiments from a local scale to a national scale [45,52]. These studies highlight the current insufficiencies, which generates high uncertainty and unresolved issues in terms of infrastructure implementation. In summary, challenges appear for the regulatory and legal frameworks of several countries and regions that are already on the path of technological transition.

On the other hand, the literature highlights the need to intensify case studies on two fronts: the adoption of hydrogen technologies and the governance processes of hydrogen and e-fuel policy frameworks. On the first front, the need to continue with case studies on the adoption of fuel cell vehicles in different countries is emphasized [59,70,76,78,80]. Also, regional studies on hydrogen production and storage [17,58]. These research challenges show the positioning of advanced countries, while the works that strengthen energy production and storage come from developing countries. This is relevant, since developing countries, although they have significant natural sources of renewable energy, show insufficiencies in terms of socio-technological development and in their strategic plans [20,57]. On the second front, the challenges lie in the development of the legislative and regulatory frameworks of transnational spaces such as the European Union, especially in transport systems [77], in the storage and introduction of hydrogen in established energy systems [63], in innovation [18] and in technology transfer between developed European and non-European countries, which still have sectors with little access [16,67].

Finally, the challenges surrounding community governance processes are related to the organizational structures necessary for their implementation [64], the adoption of specific technologies, such as fuel cells [66], and the citizen awareness in the development of hydrogen infrastructure [65]. This set of challenges would make it possible to directly address the regulatory processes for the implementation of hydrogen in the most consolidated countries in the matter, as well as in those that are just beginning their path towards this type of energy transition.

The research challenges on social acceptance and willingness to use associated green hydrogen technologies promote studies that go beyond work on transportation, especially private vehicles [68,71,81,88,93], expanding it to other fields that allow a better understanding of social acceptance and market demands [96]. Another challenge is the need for research on the social dimension of sustainability to integrate aspects that go beyond social acceptance and problematize aspects such as the impact that the incorporation of this type of technology has on the current labor market and future. Also, addressing the disconnect between intention and actual action is necessary to create public demand for new innovations (e.g., hydrogen fuel cell vehicles). If this is left solely to market forces, the speed of adoption of these technologies will be very slow [92].

Proper handling of low public acceptance and attitudes is crucial for a successful introduction of fuel cell vehicles [92]. Beyond the end user, the supply is important to achieve a social balance on these innovations. Emphasis is also placed on the importance of future studies on the acceptance of green hydrogen. Finally, the lack of familiarity with this technology in many cases constitutes a limitation when evaluating its acceptance [30]. One of the challenges that arises in this area are studies with greater depth in the specific characteristics that determine the support or rejection of these technologies. Thus, it is interesting to offer clearer interpretations about the differences in the acceptance of hydrogen between countries [30].

Our findings highlight the relevance of the social variable during the different stages involved in the green hydrogen planning process to be more effective in the long term.

This has clear implications on society by stressing the need for a more integrative and participatory process in the green hydrogen development and implementation.

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