ARTICLE IN PRESS

International Journal of Hydrogen Energy xxx (xxxx) xxx

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

journal homepage: www.elsevier.com/locate/he

Review Article

Identifying social aspects related to the hydrogen economy: Review, synthesis, and research perspectives

Sofía De-León Almaraz [a,*], Tamás Kocsis [b], Catherine Azzaro-Pantel [c], Zoltán Oszkár Szántó [d]

[a] Corvinus University of Budapest, Institute of Operations and Decision Sciences, 8 Fővám tér. 1093 Budapest, Hungary
[b] Corvinus University of Budapest. Institute of Sustainable Development, 8 Fővám tér. 1093 Budapest, Hungary
[c] Université de Toulouse, Laboratoire de Génie Chimique, CNRS, INPT, UPS, allée Emile Monso, 31432 Toulouse, France
[d] Corvinus University of Budapest, Corvinus Institute for Advanced Studies (CIAS), 8 Fővám tér. 1093 Budapest, Hungary

ARTICLE INFO

Keywords:
Hydrogen
Social aspects
Social sustainability
Social dimensions
Hydrogen economy
Systematic hybrid literature review

ABSTRACT

Energy transition will reshape the power sector, and hydrogen is a key energy carrier that could contribute to energy security. The inclusion of sustainability criteria is crucial for the adequate design/deployment of resilient hydrogen networks. While cost and environmental metrics are commonly included in hydrogen models, social aspects are rarely considered. This paper aims to identify the social criteria related to the hydrogen economy by using a systematic hybrid literature review. The main contribution is the identification of twelve social aspects which are described, ranked, and discussed. "Accessibility", "Information", "H_2 markets", and "Acceptability" are now emerging as the main themes of hydrogen-related social research. Identified gaps are e.g., lack of the definition of the value of H_2 for society, insufficient research for "socio-political" aspects (e.g., geopolitics, wellbeing), scarce application of social lifecycle assessment, and the low amount of works with a focus on social practices and cultural issues.

1. Introduction

The energy sector is at a critical stage in terms of demand and global environmental issues [1]. In Europe there are plans to achieve climate neutrality by 2050 through the Paris Agreement [2] and social factors should be considered when trying to achieve the objectives of programs such the European Green Deal and its "Fit for 55" package to enable the EU to meet decarbonisation targets. Moreover, some geopolitical conditions are important factors in terms of fostering or blocking the energy transition – for example, in the "REPowerEU" plan (May 2022) there are new objectives and strategies aimed at rapidly reducing dependence on Russian fossil fuels [3]. Renewables intermittency has been a limitation to the penetration of renewable energy sources (RES) in the energy mix. To meet this challenge, hydrogen (H_2) represents a promising alternative to recover the overproduction of electricity (e.g., from solar and wind parks) creating greater flexibility in energy systems [4].

Hydrogen is one of the most prominent energy carriers in the public, and will play an important role in the green energy transition [5]. H_2 is currently used in industry and produced from fossil fuels but it is expected to increase its presence in the mobility and building sectors in the next decades, and projected to be produced as a low-carbon fuel [6]. Roadmaps and national plans for the development of the hydrogen economy have been developed by many countries with deployment targets, in the most of the cases, starting from 2030 [7]. Its potentially new applications will affect human activities and represent a cultural transition. Indeed, the hydrogen economy will require market development associated with increasing demand and the access of people to hydrogen infrastructure. The evolution of the hydrogen economy depends on many factors and a large quantity and diversity of approaches to it can be found in the literature in different fields. Of the three dimensions of sustainability, economic and environmental factors are often used in research to compare hydrogen (or hydrogen technology) to the currently used fossil fuels by using, for example, cost or carbon footprint indicators. It is often found that the global hydrogen energy models are dominated by a techno-economic modelling approach, meaning that they aim to reduce overall system costs, although the "least costs future" might be not the one most desired by society [8].

In our experience, there is a multilevel perspective regarding social aspects in the hydrogen economy and the latter can be presented in many different ways depending on the scientific field. However, the

* Corresponding author.
E-mail addresses: de.sofia@uni-corvinus.hu (S. De-León Almaraz), tamas.kocsis@uni-corvinus.hu (T. Kocsis), catherine.azzaropantel@toulouse-inp.fr (C. Azzaro-Pantel), z.o.szanto@uni-corvinus.hu (Z.O. Szántó).

https://doi.org/10.1016/j.ijhydene.2023.10.043
Received 22 May 2023; Received in revised form 18 August 2023; Accepted 4 October 2023

research on this topic is fragmentary and the focus can be put on the socio-technological or socio-economic aspects of hydrogen [9]. A simple search for social aspects related to the hydrogen supply chain reveals some of the former but there is no agreement on the most relevant ones. Some researchers focus, for example, on hydrogen "acceptability" while others discuss global aspects like "people's place attachment" and its relationship with the energy transition. However, there are other wider frameworks that are rather generic from which some dimensions, categories, and operational indicators may be extrapolated for use in models and research on the hydrogen economy. The Sustainable Development Goals (SDG) [10,11], in addition to SDG 7 (affordable and clean energy) and SDG 13 (climate action), incorporate aspects that could be related to the energy transition and society, such as in SDG 9 (industry, innovation and infrastructure), and SDG 5 (gender equality), etc. To display another example, the "Social Futuring" framework proposes the use of the Social Futuring Index (SFI), wherein visions from different fields of the social sciences (philosophy, psychology, sociology, political theory, geopolitics …) are proposed to academia and policymakers. The SFI can be used to define and promote "a good life in a unity of order" for different countries [12], and uses wide categories that can be connected to the topic of energy. Another global approach that may be applied to human development is "social sustainability", which is defined by Harris and Goodwin [13] as "progress toward enabling all human beings to satisfy their essential needs: to achieve a reasonable level of comfort; to live lives of meaning and interest; and to share fairly in opportunities for health and education". Other aspects included in some papers are safety, human rights, and labour issues [14]. Some of the above-mentioned terms are used in the field of supply chain management, wherein four social aspects associated with social sustainability are proposed by the Global Reporting Initiative (GRI): Human Rights, Labour Conditions, Society and Product Responsibility [14–16]. In operations and supply chain management, the most used frameworks are "social sustainability" together with "corporate social responsibility" (CSR), and more recently the "social lifecycle assessment" (S-LCA) [16,17].

However, measuring sustainability and quantifying the social dimension of sustainability are difficult tasks due to the lack of agreement on an objective definition of social sustainability [18]. The scientific community still avoids the usage of social indicators due to the lack of consensus; they are subjectively perceived and difficult to evaluate [17]. Some dimensions or indices from the abovementioned frameworks may be found in hydrogen-related research papers that discuss specific social topics (e.g. Refs. [19–21]). To avoid confusion, in this paper we use the term "social sustainability" from the perspectives of operations and supply chain management with dimensions from the GRI approach, and we limit our analysis to the identification of the "social aspects" of the hydrogen economy.

"Social aspect", "social issue", and "social criterion" are often used synonymously. A definition of social issues in the supply chain is provided by Ref. [22] as the "product/process-related aspects of operations that affect human safety, welfare and community development", using metrics such as health and safety, product safety, economic welfare, and growth. More social impacts associated with hydrogen fuel or its technologies are child labour and health expenditure, labour rights, health and safety, human rights, governance, and community infrastructure, the dignity and rights of humankind, political stability, resilience, social acceptance, social cost-benefit analysis, governmental policies, etc. [23]. With these large number of variables, it may be difficult to identify the social indicators or factors that are appropriate for study in the hydrogen economy, and to select whether to use qualitative or quantitative methodologies in a multisectoral context. Given the complexity of the topic, the treatment of interrelations with multiple dimensions is often found in publications that report on two or more social aspects.

There are a few review papers that connect social aspects to the hydrogen economy [24–27]. It is identified the need for multidisciplinary teams to discuss social aspects related to hydrogen technology. The work of Krumm et al. (2022) [8] highlights that better representation of social aspects in energy models is essential for understanding the effects of the drivers and constraints of renewable energy technologies (and hydrogen), including the effects of societal paradigm changes, on the speed of the transition and redesign of the energy system. In this sense, interdisciplinary work, especially from engineers, sociologists, psychologists, etc. is of fundamental importance in research, partly for informing modellers who can connect and integrate different views about social dynamics into their models. The same work [8] concludes that studies presently lack interdisciplinary collaboration between modellers and social scientists, and hardly integrate any insights from social science such as theories. In addition, some of the abovementioned reviews use bibliometric analysis. In our experience, the use of the bibliometric review allows the identification of hotspots but additional efforts are needed to allow a clear identification of the social aspects.

Thus, the contribution of our multidisciplinary team is to identify, through a systematic literature review, that includes both, bibliometric and structured literature reviews [28], the current state-of-the-art regarding social aspects in the hydrogen economy in a broader sense. In this paper, the social aspects (also referred as social dimensions and social factors) of the hydrogen economy will be defined as all aspects that concern people and their interactions and relationships within a hydrogen system (adapted from Ref. [8]). The scope of this review is not only social sustainability issues related to firms working with hydrogen but identifying all the social perspectives that have been considered in the development and deployment of the hydrogen economy until now as reflected in scientific papers.

In that sense, the main research question of this review is: what are the main social aspects related to the hydrogen economy?

By following a multidisciplinary effort, the scientific objectives of this review are thus:

- To identify the main social aspects related to the hydrogen economy (according to recent research)
- To synthesize the state-of-the-art research on this topic
- To detect related research gaps, and
- To propose research avenues to the domain for the future

This paper is organised as follows, Section 2 presents the proposed methodology for our systematic literature review (SLR); Section 3 is dedicated to the development of the literature review analysis and identification of main social categories for defining and organising the social aspects in a structured way. The results from the literature review are analysed in Section 4 followed by the identification of the gaps and the presentation of perspectives based on expert opinion and additional sources (Section 5). The conclusions of this review are available in Section 6.

2. Methodology

In this section we describe the methodology used to synthesize current knowledge, identify research gaps, and suggest new directions for future research in the field of the hydrogen economy with a focus on the related social aspects. A summary of the framework is presented in Fig. 1, involving three main stages.

(I) Topic and resource identification;
(II) Systematic literature review (Section 3);
(III) Summary and report of results (Sections 4 and 5).

A brief description of the steps is given in Sections 2.1-3.

2.1. Topic and resource identification

- Step I.1. Define topic: social aspects in the hydrogen economy
- Step I.2. Formulate research question:

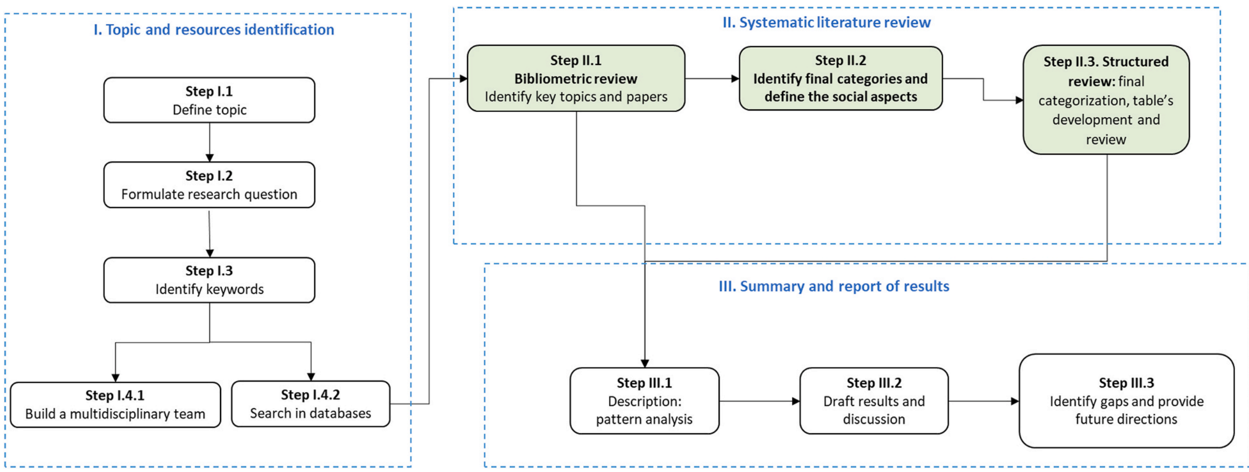

Fig. 1. Structure of research methodology.

- what are the main social aspects related to the hydrogen economy?
- Step I.3. Identify keywords in titles:
  - "Hydrogen" OR "H_2" AND
  - "social" OR "socio*" OR "soc*" (the last term is used to find generic words, e.g., society, sociotechnical, societal …)
- Step I.4. Resources:
  - Web of Science (WoS - core collection) and Scopus databases. These are the most extensively used databases. In previous reviews, some authors decided to use only Scopus [29] or Web of Science [30]. However, there is not an identical outcome from the two databases when using the same search keywords so when using a single database, it cannot be ensured that all high-quality publications were included. Therefore, even if some technical difficulties are associated with the combination of the two databases for the bibliometric evaluation [31], in this work both, Scopus and Web of Science databases, are used.
  - VOS viewer. There are several software packages for bibliometric analysis, e.g., R studio (Biblioshiny), Cite space, Gephi, Bib Excel, Histcite, and VOS viewer [31]. VOS viewer is widely used for cluster analysis due to its ability to interpret data from reference managers, Scopus, WoS, etc. [29,30,32]. VOS viewer was selected for the bibliometric analysis because is a free, user friendly, and simple environment that allows the identification of trends [33]. The VOS viewer is used to enable a clear, organized, and systematic review by reducing the subjective biases. Through the clusters it is possible to identify large categories as a prerequisite to the structured review.
  - Mendeley is used as a reference manager due to its practicality as a common tool among the researchers to compile all the articles, to add the PDFs, and to manage the references in Word. No duplicates are added to the Mendeley library.
  - Excel and Word (data treatment and structural review). The outcomes from Scopus and WoS databases are downloaded in format csv. Microsoft Excel is used for data treatment and analysis. The csv files are merged in Scopus format. As a second step, Excel is used to classify the terms and to quantify the occurrence. All the used files are presented in Excel (see Supplementary Material: "H2Social"). Word is used to report the outcomes.
- Step I.4.1. Build a multidisciplinary team

The research was developed in coordination with three research groups with four team members with complementary backgrounds: a chemical engineer from the Chemical Engineering Laboratory from the University of Toulouse; an economist/social scientist from the Institute of Sustainable Development of Corvinus University of Budapest; an economist/social scientist from the Corvinus Institute for Advanced Studies; an industrial engineer from the Institute of Operations and Decision Sciences (Supply Chain Management) of Corvinus University of Budapest.

- Step I.4.2. Search in databases

The research flow was implemented in August 2023 and the specifications are displayed in Fig. 2. The documents from Web of Science and Scopus were filtered and only research and review articles in English were selected. A total of 47 documents were available from both databases. Papers from 2000 to August 2023 were selected. The final selection imported into Mendeley and used in the bibliometric analysis contained 65 documents (listed in Supplementary Material: "H2social").

2.2. *Systematic literature review (SLR)*

This systematic literature review is domain-based, with a hybrid form integrating the tenets of both bibliometric and structured reviews [28]. The general structure of the SLR is displayed in Figs. 1 and 3.

- Step II.1. Bibliometric review: this type of analysis has become an important research tool. Several hydrogen reviews have used the bibliometric approach to develop maps and frameworks supporting the synthesis, analysis, and conclusions stages [29,32,34]. The main enablers to have meaningful bibliometric reviews are: (1) the increased availability of internet databases, (2) the development of analytic software that allows the examination of big databases (quantification, standardization, mapping), (3) the mitigation of subjectivity; (4) identification of research trends among other analyses [29,32,34]. In this work, a graphical bibliometric analysis was developed using *VOS viewer* [33] to identify trends and relationships associated with the words in title, abstract and keywords (Appendix A).
- Step II.2. Identify final categories and define the social aspects: the initial categories were defined based on maps of the bibliographic review, and the final (large) categories were defined based on experts' analysis. These large categories are also called "social aspects" (Section 3.2).
- Step II.3. Structured review: in this step, the articles are revised by the experts who analyse title, abstract and keywords fields and identify social indicators, functions, or terms with regards to the "social aspects" definitions. After this final categorisation, a

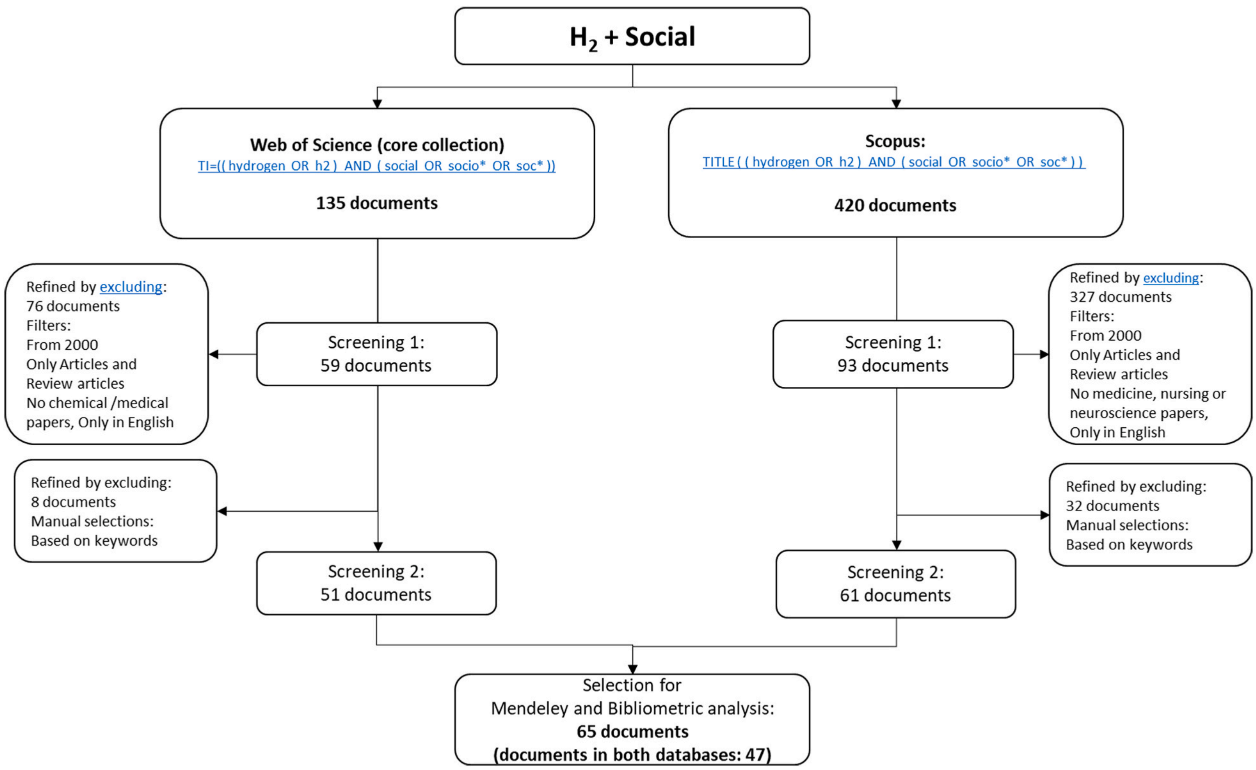

Fig. 2. Research flow in Web of Science and Scopus (search date August 03, 2023).

summary table is developed (Appendix B). Finally, the occurrence of the different social aspects is analysed and ranked (Section 3.3).

2.3. Summarizing, and reporting the results

- Step III.1. Description: the outcomes of bibliographic and structural reviews were analysed and the graphs, tables and figures revised and organised. Trends and perspectives were highlighted to cover gaps in the current state-of-the-art and described for each category (Section 3.3).
- Step III.2. Draft results and discussion of papers from the SLR (Section 4).
- Step III.3. Identify gaps and suggest directions for bridging the gaps. As a form of benchmark, some perspectives are based on reference papers that study social aspects in other fields (Section 5).

3. Implementation of the systematic literature review

The 65 articles identified by following the protocol from Fig. 2 are part of the rigorous SLR. The table "JournalsSummary" from the Supplementary Material illustrates that 44 % of the original research and review articles were published in the International Journal of Hydrogen Energy (29 papers), followed by 6 % from Energy Research & Social Science (4 papers) which has a more social orientation. In the rest of the list, most of the journals are oriented principally to technical or engineering issues.

3.1. Bibliometric review

For the bibliometric analysis, several maps were built to facilitate a first examination based on the visualisation of key clusters and identify large categories of social aspects. The mapping creation consists of an iterative process where the maps can be refined gradually. In our research we have follow a rigorous analysis of the maps and used thesaurus files to capture the main categories from the sample (mapping protocols and details are available in Appendix A). The VOS viewer allowed the creation of maps by using the following criteria:

For the mapping plan the analysis is done at three levels.

- Title and abstract maps
- Authors keywords map
- Social aspects map

Due to the heterogeneity in the database the researchers proposed new labels for large categories that can be representative to the data. In this sense, the bibliometric maps (in Appendix A) were used just as a reference to preselect categories, analyse them, choose the best large categories, and provide a definition to them as displayed in the next section.

3.2. Definition of the selected social aspects

For Step II.2 (Fig. 3), a list of the 49 potential categories was used as the starting point for the identification of large categories (Supplementary Material: "Biblio_Occurrence"). The experts revised the potential categories, discussed if they might be considered large categories or subcategories, and labelled them accordingly. In this exercise, the occurrence analysis was not the main criterion for selecting large categories; instead, the term meaning was the most relevant criterion. For instance, "information", with a total of 13 occurrences, was selected as a large category and includes the subcategories of "awareness - carbon footprint" (occurrence: 67), "education" (occurrence: 5), "knowledge" (occurrence: 25), and many others. For this example, the subcategories represent terms for using or spreading information, being the "information" the common aspect and, in that sense, the large category to represent a social aspect. By applying this methodology, a total of 12

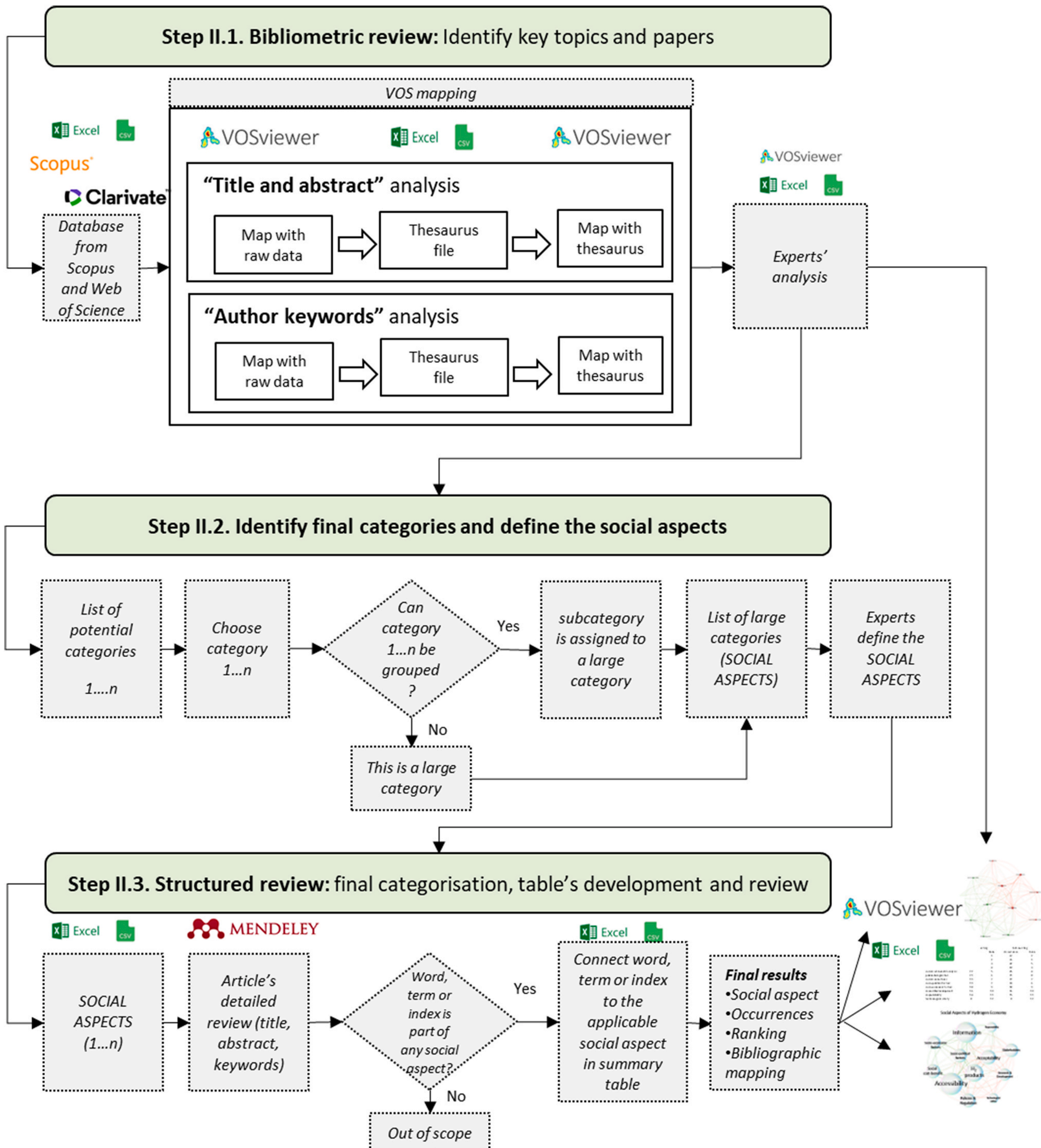

Fig. 3. Systematic literature review methodology.

social aspects have been retained and their descriptions were developed by the research team (Table 1). This task was crucial to allow the right assignation of indices, terms, or metrics to the most appropriate social aspect as explained in the next section.

3.3. Structured review

The title, abstract and keywords from the 65 papers have been analysed. Words, terms, and indices are classified into one of the 12 social aspects. Synonyms and similar words/indices have been placed together to avoid duplications. An advantage of using this method compared to the bibliometric review is that the raw data can be connected to the article's information so a deeper analysis can take place and the data can be validated or tracked back. The outcome is reported in the form of tables (Appendix B and Supplementary Material: "StructuredReview" and "H2social_categories"), and the emerging framework from the structured review is given in Fig. 4.

The structured review allowed the development of the final map for social aspects incorporated into the hydrogen research (Fig. 5). The

Table 1
Social aspects - descriptions.

Aspect	Description
Acceptability	Acceptability affects the H_2 demand. Several factors of H_2 markets and infrastructure are subject to acceptance or opposition for use and/or consumption. Six key elements are included: acceptability (usually measured using questionnaires and surveys), psychology, willingness-to-accept, -pay, -use, or –purchase, consumer behaviour, attitudes toward land usage, and the analysis of socio-demographic factors in relation to the purchase intention.
Accessibility	Accessibility to hydrogen products and infrastructure is the quality of being able to easily reach, obtain, buy, and use hydrogen, and its associated technologies. The accessibility to hydrogen technologies is an umbrella concept in which three different key elements infrastructure accessibility, H_2 affordability and FCEV affordability are included and cover several issues (technology needs, technology design, hydrogen supply chain design, hydrogen and fuel-cell vehicles cost/price, capacity-building, and infrastructure location).
H_2 markets	The "H_2 markets" are related to H_2 physical goods that will be bought or used by users in different parts of the hydrogen supply chain. There are three main market sectors mentioned: mobility, industry, and residential use. This category includes H_2 fuel expected to be used by end users (e.g., kilograms of "green" hydrogen). Other H_2 markets like those of fuel cells, electrolysers, fuel cell cars or trucks are also included here.
Information	Information is an immaterial resource used to share news, data, learnings, and knowledge in the community. This category includes terms related to the level of information and awareness in society regarding hydrogen fuel, H_2 technologies, and carbon footprint. Discourse, education, and knowledge are also part of this category. The use of information might vary, for example, technical knowledge is gained in education and research centres or industry while more generic information is spread to the general public using different communication tools.
Policies & Regulation	A policy is established at an organizational level listing rules to achieve specific organizational goals. The development of policies is done by the different stakeholders of the hydrogen supply chain (e.g., companies, government, etc.). Regulations are prescribed by authorities and are rules or restrictions with the effect of a law to make people and organisations follow certain rules. Organisations that enter new markets may encounter relatively lenient regulations related to product disposal and consumer health and safety and this might be the case for hydrogen operations in several topics but especially in those related to quality and safety.
Research & Development	Research & Development includes activities that academia, companies, laboratories and research centres undertake to design, develop, improve, innovate and introduce new H_2 markets or services.
Responsibility	Responsibility includes management issues related to all types of organisations working with hydrogen products and technology. Examples of the terms added to this category are risk management, implementation, S-LCA, social responsibility, sustainability, SDGs, and working conditions.
Stakeholders	Social connections among stakeholders are necessary in the hydrogen economy deployment. A stakeholder is a party, entity or actor that has an interest and can affect one or several operations of the hydrogen supply chain. Some examples are producers, distributors, investors, customers, suppliers, government, etc.
Externalities	Externalities are included in social cost-benefit analysis (SCBA) that is a quantitative, monetized metric to present the total positive or negative costs and benefits of investing in hydrogen technologies. SCBA captures different stakeholders' points of view by including financial analysis for decision makers (infrastructure, fuel cost, the total cost of ownership, etc.) and externalities where different sustainability related societal costs and benefits can be included (e.g., reducing/increasing GHG emissions, air pollution, noise, etc.).
Socio-economic factors	Socio-economic factors involve financial and other societal status factors including income, taxes, subsidies, job opportunities, social development indices (e.g., Human Development Index).
Socio-political factors	Socio-political factors include: living environment, security, quality of life, wellbeing, equality, social integration and participation, international relations, and political conflicts. For the specific case of hydrogen, energy security and energy justice are in this category.
Technological safety	Safety is the condition of being protected from or unlikely to cause danger, risk, or injury while producing, transporting, storing, distributing or using H_2 products.

ranking of the social aspects was found by using the occurrence metric[1] of the large categories as displayed in Table 2. This ranking cannot be generalised in terms of the importance of the social aspects, and it is used only to highlight the main trends in terms of occurrence from which "accessibility", "information" and "H_2 markets" are the top 3 categories.

4. Social aspects – descriptive analysis

The description of the results is given here by highlighting the key elements of the state-of-the-art, and then, specific gaps found from the critical analysis from this section are listed in Section 5.

4.1. Accessibility

The first social aspect addresses the access to hydrogen and its infrastructure; 88 % of the articles mentioned terms related to the availability or affordability of infrastructure, products, or hydrogen supply chains. Since the number of articles referring to this category is large, the summary of the results is given here with the identification of the subcategories only for some of the citing works. Details for each article from this category are presented in Appendix B and Supplementary Material: "StructuredReview".

To make hydrogen available, it is crucial to ensure that a large-scale infrastructure for production, storage and transportation is installed to cover the demand [35–39]. Moreover, access to green hydrogen is strongly related to the availability of renewable energy sources [40–44].

This social aspect is somehow connected to the maturity of H_2 technology. In this sense, there are efforts to improve the process efficiency for water electrolysis, and new materials are being tested. In addition, carbon capture and storage (CCS) can be used when hydrogen is produced from fossil sources [24,45–48]. Although, access to CCS technology is yet limited and expensive, its deployment could increase flexibility, not just for H_2, but also for other energy systems. However, the stored CO_2 should be somehow used if a circular approach is expected.

The infrastructure impact is studied in several works that propose demand-driven models to optimise the cost, environmental impact, or safety of hydrogen supply chains (HSCs) [49]. A discussed topic is the

[1] More information: Supplementary material: "Summary Tables". The binary counting [133] was used to avoid duplications because the occurrences attribute indicates the number of documents in which a social aspect occurs at least once due to the fact that in some papers several terms are used as synonyms to treat a same topic, e.g., "public perception", "social acceptability", "willingness to pay" are all related to the large category "acceptability". With the full counting method, the occurrence is 3 whereas with the binary counting the occurrence is only 1. Our chose to use binary counting does not affect the outcome because this ranking was used only for reporting purposes and not to define the importance of the social aspects.

[2] Although the ranking cannot be generalised, it can highlight the most/less popular research areas for social aspects of the hydrogen economy.

[3] Size of objects are proportional to the occurrence, links found in VOS viewer. More details available in Appendix A (Map 4).

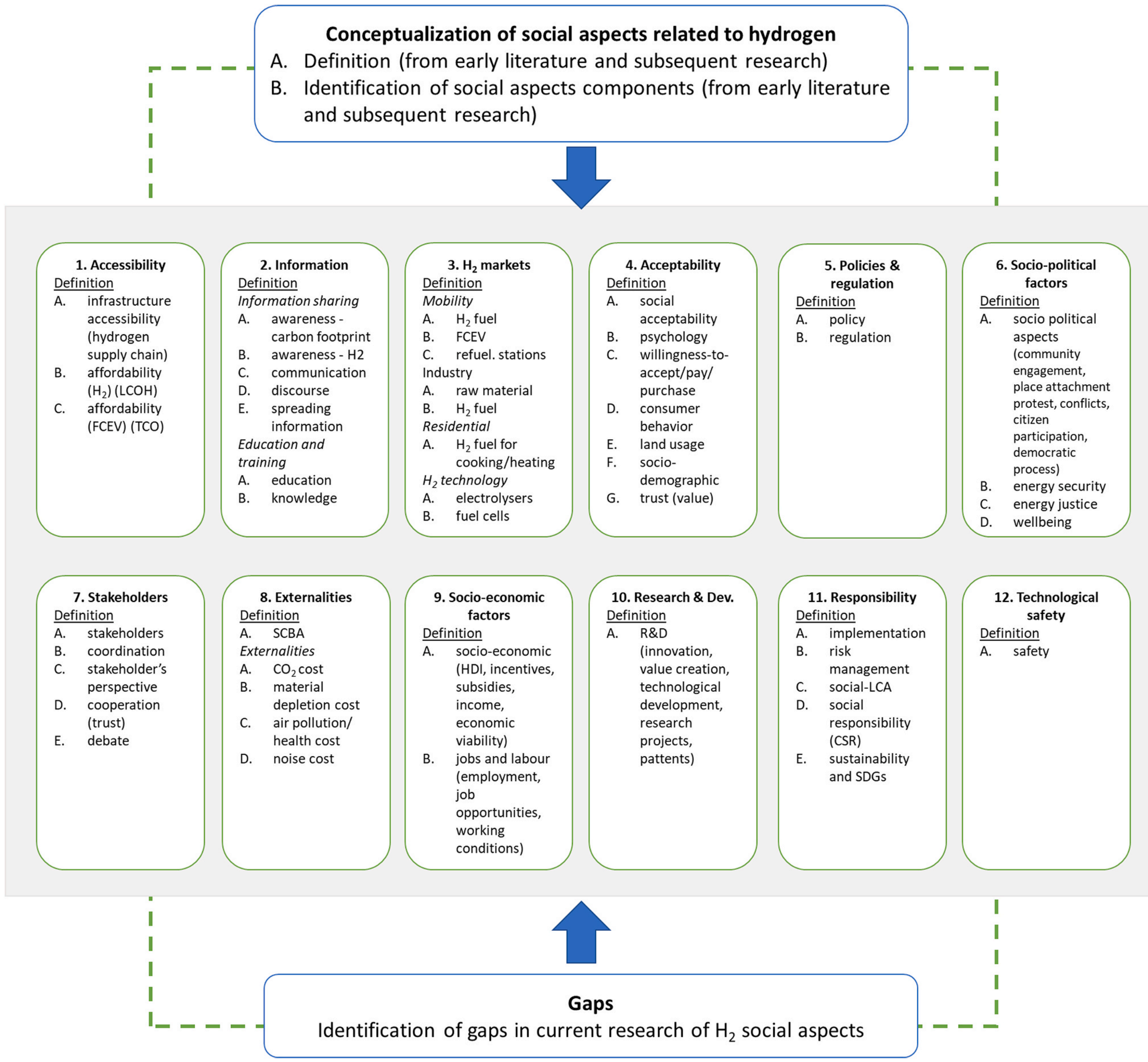

Fig. 4. Emerging framework: social aspects related to the hydrogen economy.

possibility to refurbishing existing facilities use for natural gas (e.g., pipelines) [50] or installing new ones. Facilities' location is also highlighted as an essential factor for HSCs because of its impact on hydrogen price. Particular emphasis is given to the access to refuelling stations and storage centres which are expected to be strategically located along the road network[4].

The H_2 cost/price is labelled in our research as "affordability – H_2" [36,51–53]. In this case, the access to hydrogen depends on the price people must pay for 1 kg of hydrogen depending on the levelized cost of hydrogen (LCOH) for different hydrogen types (e.g., green, blue, gas or liquid). The LCOH is cited in papers that stress the importance of cost-competitiveness and its relationship with social acceptability.

Finally, the "affordability of fuel cell electric vehicles" is also a topic discussed with a particular focus on the vehicle's capital cost, maintenance, and the total cost of ownership (TCO). A competitive TCO can be a key factor in the end user's decision-making [35,36,49,54].

[4] This point can be measured through the average distance to the point of access of the product.

4.2. Information

The second social aspect is access to information; 85 % of the papers mention terms belonging to this category. "Information" includes terms related to six subcategories which can be split into two groups. The first group represents gaining or sharing information from several means in a relatively informal manner (general public): "awareness - carbon footprint", "awareness - H_2", "communication", "discourse" and "spreading information". The second group includes information that is formally and systematically generated and shared from/to students, workers, or experts: education and knowledge (see Appendix B for details on subcategories and citing articles).

Several papers discuss the relationship between awareness level and acceptability. Environmental awareness (awareness - carbon footprint) has been the category with more occurrences from our sample (e.g. Refs. [25,35,40,42,45,48,51,55–61]). Examples of words included are decarbonisation, GHG emissions, GWP, climate change, zero emissions, life-cycle emissions, ecological, carbon-free society, and carbon targets. Not surprisingly, many papers include these words as part of the justification for deploying RES coupled with hydrogen. The reason is that

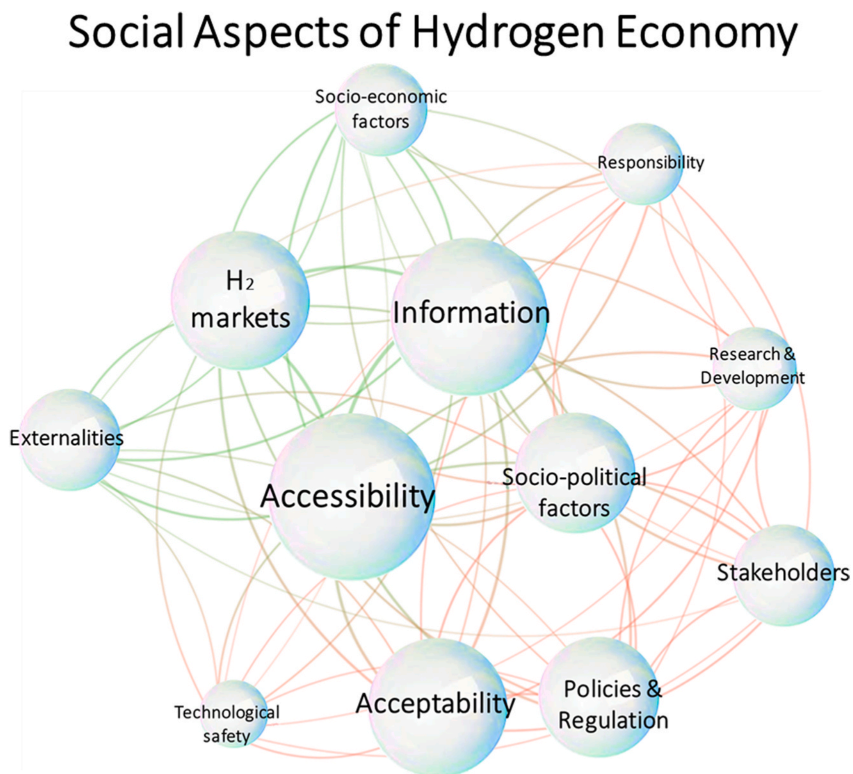

Fig. 5. Social aspects reported in hydrogen research.[3]

Table 2
Rank of categories related to social aspects.

Social aspect	Occurrence	Rank[2]
accessibility	57	1
information	55	2
H_2 markets	44	3
acceptability	35	4
policies & regulation	26	5
socio-political factors	26	6
stakeholders	24	7
externalities	22	8
socio-economic factors	21	9
research & development	19	10
responsibility	19	11
technological safety	14	12

green hydrogen might results in lower greenhouse gas emissions. It can be expected that different population groups (e.g., age, gender, education level) could have different levels of awareness about the negative environmental consequences of using fossil fuels and the positive effects of RES and hydrogen. Some papers are explicitly dedicated to the awareness of hydrogen risks and benefits ("awareness - H_2") [19,47,62].

Other subcategories are the use of media support and communication tools ("communication"); the narrative, criticism, and discourse ("discourse"); and public relations campaigns ("spreading information") [63–65].

Information shared or documented formally is paramount to society. "Knowledge" and "education" are related subcategories [38,45,66,67]. Knowledge can be shared in educational and research institutions or workplaces in the form of books, reports and articles, training, courses, workshops, conferences, etc. It is the result of social constructed symbolic systems and orders, produced in and by discourses [47]. One example can be the technical knowledge and skills needed by engineers for developing or improving hydrogen technology. Although technical knowledge of hydrogen has been prioritised in the last decades, more studies highlight the relevance of developing knowledge in other areas, e.g., social science. The knowledge resulting from hydrogen projects can be shared to increase social awareness not only related to hydrogen attributes but also other topics like lifestyle footprints [68].

Issues rarely mentioned are transparency and traceability of information [47]. A specific example of the importance of these topics is the need to know the origin of the energy sources used to produce hydrogen and the associated technology to calculate the related costs, risks, and environmental impacts and to inform the final customer (e.g., guarantees of origin).

4.3. H_2 markets

The energy transition will result in new products and applications. The H_2 products are those physical goods that will be bought or utilized by users in different parts of the hydrogen supply chain. Today, H_2 products can be listed for different markets as follow: mobility (fuel cell electric vehicles, H_2 fuel, H_2 refuelling stations), industry (H_2 as raw material in refining or ammonia industry), H_2 technology (e.g., electrolysers, fuel cells), H_2 fuels (liquid or gaseous H_2), and residential products (H_2 fuel for cooking or heating) (see Appendix B for details on subcategories and citing articles).

From the SLR, 68 % of the papers mention a specific application of H_2 markets. However, the research topics are very diverse meaning that, in this category, H_2 products are studied from different perspectives, i.e.: market deployment, technology efficiency, safety, materials availability, product cost, consumer acceptability, policy and regulations, and information.

For the mobility products, it is emphasized that hydrogen is a clean and nontoxic fuel that can be used in private fuel cell vehicles, heavy-duty trucks, or buses so this means that society will require to get familiar with those products switching from fossil fuels mobility to green transportation through hydrogen products [69–73]. For this purpose, hydrogen refuelling stations are also products that might require several electronic and mechanical components [74–76]. In any case, producers for the different H_2 products are needed, and a robust supply chain will be needed to enable large-scale production and commercialisation of H_2 products. However, smooth market penetration is projected for the next decades (2030–2050). There is no research treating circularity aspects of H_2 products.

For the industrial market, new applications are expected in addition to the current uses in refinery, chemical and ammonia industries. Hydrogen can contribute to the decarbonisation of energy-intensive industries like iron-steel and cement sectors, partially motivated by more expensive CO_2 allowances [24,38,48,65,77]. However, more research is needed to measure the cost-benefit of such alternatives.

Only three papers referred to the home use of H_2 products. In this case, hydrogen is tested for heating and cooking applications with a focus on customer experience and acceptability [50,78,79]. More research is needed on social practice.

4.4. Acceptability

One of the most studied social categories is public or social acceptability of H_2 markets and infrastructure. Social acceptance is vital for the hydrogen economy due to its relationship with demand [23]; 54 % of the papers discuss hydrogen acceptability, but different perspectives are given.

In many cases, acceptability studies are carried out at the country level where social acceptance may be affected by people's attitudes and perceptions, lifestyles, and preferences.

Qualitative analyses using survey-based or interview methodologies coupled with statistical analysis are the most typical [19,43,47,62,69,70]. This category includes six key elements: (1) acceptability, (2) psychology, (3) willingness-to-accept, -pay, -use, or –purchase, (4) consumer behaviour, (5) attitudes toward land usage, and (6) relationship between socio-demographic factors and acceptance (Appendix B).

The terms included in the "acceptability" subcategory are: social/public/societal/customer/market/technology acceptance [acceptability], social barriers/opposition/support, social/customer preferences, etc.

Many papers discussing acceptability relate this issue to "psychological aspects" because perception, attitude, satisfaction, concerns, and levels of trust, have a repercussion on the psychosocial dynamics that guide society to a given "behaviour" [26,67]. Upham et al. [38] studied expectations about new hydrogen technologies and proposed a framework that connects individual psychology to practice. In this sense, some papers highlight that increasing energy consumption is the expected social behaviour. In addition, green buying behaviour and new social practices related to H_2 use (e.g., transport, heating and cooking) are also explored [80]. Some articles discuss acceptability measurement through "willingness-to-pay", "accept", or "purchase" [35,37,52,70].

"Socio-demographic" information is typically collected in studies that include qualitative research through surveys where factors such as gender, age, education, and income are generally analysed. Scott and Powells [79] report that the acceptance of hydrogen is often positively correlated with higher education, stronger environmental values, and greater trust in technology, with men more likely to know more about hydrogen than women. Huijts and van Wee [75] report that psychological variables explain public acceptability better than socio-demographic variables for refuelling stations.

Finally, it is found that opposition is sometimes related to "land usage" of new facilities needed to produce, store, and distribute H_2. But it can also be connected to the need to develop additional capacity for renewable energy sources. Some people oppose the installation of refuelling stations or production plants in their proximity. These opposition behaviours are described as "Not In My Backyard" (NIMBY) objections [81].

4.5. Policies & regulation

Policy and regulation are intangible drivers often presented together; 40 % of the papers include at least a comment on this social aspect. Organisations that enter new markets will need policy and regulatory to support the implementation and scale-up phases.

A policy is established at an organisational level, listing rules to achieve specific organisational goals. The development of "policies" is done by the different stakeholders of the HSC (e.g., companies, government, etc.). Stakeholders might be partly conditioned by their socio-economic and innovation policy context [38]. The collective perspectives of different stakeholders can be restructured to reduce conflict in policy decisions [25,82].

Hydrogen policy aims at promoting investment in both hydrogen technology and infrastructure. It starts with the policy announcement and moves to public awareness, demonstration and R&D projects [66,70]. Hydrogen policy is closely related to energy policy for decarbonisation to contribute to the worldwide transition to a low carbon economy by 2050 (e.g., EU Energy and Climate Policy) [35,83].

Furthermore, public policy can encourage the increase of H_2 demand because through it, H_2 technology and products could be more accessible and public acceptance might increase [35,38,66]. Specific policies for constructing facilities might include "land use" and feasibility considerations. An example for the construction of refuelling stations is given in Ref. [84]. Policy-making can be supported by SCBA, which may highlight the need for subsidies [36,38,85]. In addition, policy efforts in technology and R&D can be associated with funding (e.g., Clean Hydrogen Partnership) or public-private partnerships where the social connection between industry and government is vital for supporting policy and regulation. Moreover, Griffiths et al. [24] present a summary of policy relevant to hydrogen socio-technical systems. Financial policies (e.g., tax exemptions) could also support the development of hydrogen as done in the biofuels sector (e.g., quotas as a part of the updated Renewable Energy Directive (EU)2018/2001 (RED II)) [48].

In addition, "regulations" prescribed by authorities act as rules or restrictions with the effect of a law to make people and organisations follow certain rules to keep the system regulated. They are part of the legislative framework. An example of an international regulatory organisation is the International Energy Agency (IEA). This type of organisation help create the value proposition for hydrogen and build public confidence [52].

Besides, Griffiths et al. [24] present a summary of regulatory mechanisms to allow standards for CO_2 emissions, energy use, electricity generation, certifications schemes (third-party verification of HSC carbon footprint, e.g., EU CertifHy; EU Revised RED II, guarantee of origins, etc.), safety, quality performance, and price controls (cap and floor). In the last years, the colour of hydrogen has been a source of confusion, today, efforts to clarify what exactly is "green hydrogen", are taking place, e.g., the European Commission introduced new terms like "low carbon hydrogen", "renewable hydrogen" or "Renewable Fuels of Non-Biological Origin (RFNBOs)" [86] to avoid confusion.

4.6. Socio-political factors

Including the socio-political dimension is also of utmost importance for the hydrogen economy deployment. From the SLR, 40 % of the articles mention some "socio-political" concepts. General terms included here are: political analysis, community engagement, protests, conflicts in society, citizen participation and democratic processes [44,83,87–89].

Some authors include comments for the "energy security" subcategory, where hydrogen can play an essential role in decreasing or changing the energy dependence on fossil fuels and neighbouring countries [50]. Positive and controversial arguments are present regarding the security of supply [47,83]. Some measures allow us to track this factor. One is the domestic energy dependency index [90];

another could be the hydrogen imports/exports [42,46,52] with potential implications for societal acceptance of hydrogen.

Another topic is "place attachment", where acceptance or opposition to hydrogen technologies can be manifested through social participation. Resistance to energy infrastructures deployment (e.g., NIMBY) might be related to place attachment. Place attachment can be felt and occur at multiple scales (street, neighbourhood, town, city, region) simultaneously and in different ways, for this reason, possible acceptance or resistance to hydrogen infrastructures is sensitive to the shifting scales and sites of infrastructural change [79].

For "energy justice", Scott and Powells [78] relate experiences of fuel poverty and distributional justice, other works treating this topic are [50,67,91]. Meanwhile, Hienuki et al. [74] introduce a classification for individual and infrastructural "wellbeing". Wellbeing is based on the assumption that a healthy environment is necessary for healthy humans. Included terms in the wellbeing subcategory are: living standards, quality of life and personal wellbeing [44,83,87–89].

More research is needed around geopolitics, Akhtar et al. [92] presents a discussion of geopolitical implications emphasizing the need to develop standardized international regulations to prevent colonialism in the future hydrogen economy.

4.7. Stakeholders

Social connections among stakeholders are necessary for the hydrogen economy deployment. The SLR displayed that 37 % of the consulted literature highlights at least one of the five main topics inside this category.

The first topic is dedicated to "stakeholders" being part of an actor-network and pointing out the importance of trust and commitment for decision-makers in industry, government, policymakers and experts in the hydrogen transition [20,25,38,40,48,64,66,67,70,75,93,94].

The second topic is "coordination". In every stage of the hydrogen economy deployment, coordination and organisation are needed among the different stakeholders. For this purpose, management tools can be handy to connect the stakeholders and launch organised efforts. One example is given by Hsu and Lin [95], who use social network analysis to find relationships among patents for hydrogen production using biomass. The network analysis for this example can be followed by connecting patent developers for future research or collaboration. However, coordinating a large number of actors from different countries and entities is not easy. Many efforts are needed to optimise resources and knowledge from the different stakeholders [9,42,63,84,95]. Specific efforts to do so are made in many regions. For instance, Europe coordinates several hydrogen-related activities through the Clean Hydrogen Partnership (https://www.clean-hydrogen.europa.eu/index_en) and Hydrogen Europe (https://hydrogeneurope.eu/). Joint efforts of academics, manufacturers, politicians, workers, customers, etc., at different levels (strategic, tactical, and operational) are needed for the successful implementation and market penetration of hydrogen technologies [83]. An emerging topic is social entrepreneurship [96].

The third topic is "stakeholders' perspective", which can affect social connections, acceptability, and coordination. The actors might have divergent and heterogeneous visions, interests, desires, priorities, and objectives. These can even be, in some cases, contradictory. How, then to fill this gap between the logic of the researcher, the manufacturer, and the politician? [97]. If the stakeholders with different visions towards hydrogen can be articulated and put together, a win-win approach could occur [47,62,66,89]. An analysis of agents' dynamics can help gather varied representations and divergent interests around the same goal [38].

The last two topics are "cooperation" and "debate". Cooperation among companies and politicians is highlighted, and also among neighbouring countries [27,42,63]. In the work of Schnuelle et al. [65] it is emphasized the importance of the debate on increasing energy bills and its correlation with the energy system transition. The debate is then linked to the available information, which will determine the narratives and dialogue of stakeholders [64].

4.8. Externalities

Social cost-benefit analysis (SCBA) is a systematic method of surveying all the impacts caused by hydrogen technologies. Externalities is mentioned in 34 % of the papers. SCBA is scientifically established and widely used in policy impact assessments because is a quantitative measure expressed in monetary units [36]. It encompasses financial effects (investment and operating cost, net present value, the total cost of ownership, etc.), and societal effects like pollution, environmental impact, noise, safety, health, labour market impacts, among others.

Externalities are then considered to be "all costs and benefits that are additional to the private costs or benefits of the business case (hidden costs/benefits)" [98]. Externalities reported in the SLR include carbon costs, material depletion costs, air pollution-health costs, and noise-related costs.

In many papers, social cost, social cost-benefit, and other terms are used to refer to similar concepts however the externalities vary. To our knowledge, social cost with a focus on the siting of new refuelling facilities was first presented by Ref. [37] and the societal lifetime cost of hydrogen fuel cell vehicles was first addressed by Ref. [53], who adopted a societal welfare perspective to compare the situation of the latter with that of conventional gasoline vehicles. The SCBA for the hydrogen supply chain with a focus on FCEV vs ICV was applied using multiobjective optimisation in Refs. [36,49] by following the methodology described in Ref. [54].

Externalities coupled with optimisation models seems to be a promising approach to incorporate factors from the three sustainability dimensions into the hydrogen evaluations. However, in externalities reports there might be lack of information due to data aggregation.

4.9. Socio-economic factors

This social aspect involves financial and other societal status factors which are present in 32 % of the papers. Terms like national wealth, Human Development Index, society development, national economy indicator (GDPI), gross national product per capita, income, and development capacity indicator are included.

Fiscal incentives like subsidies and taxes have been placed in this social category and not in "policies & regulation". However, they can belong to the two aspects [36,40,45,53,68,72].

Although several reports publish details about the expected job-creation impacts of the hydrogen economy for specific countries (e.g., FCH JU2, 2020 99), very few articles that explicitly contain the words "hydrogen" and "social" deal with the topic of jobs and labour. Among them [100], offers a detailed explanation of the effects on employment for a naphtha-reforming hydrogen plant. Chapman et al. [46] present a measure on employment (FTE/technology type), and Werker et al. [20] focus on working conditions on the basis of the UN agenda 2030 Sustainable Development Goals. Depending on the level of analysis, topics related to job creation and labour could also be included in "responsibility".

4.10. Research & development (R&D)

R&D includes activities that academia, companies, laboratories, and research centres undertake to design, develop, improve, innovate, and introduce new H_2 markets or services; 29 % of the papers explicitly mention R&D. This social aspect is closely linked with education and knowledge, then high-quality education and access to information and R&D equipment are preconditions to quality in R&D activities. Technological development and innovation can lead to patents and even mass production of key component (technology transfer) where knowledge is also derived from real-world experience together with human expertise capable of transforming the knowledge into action. Since the hydrogen economy is at an early stage more and more researchers are needed for technical R&D and for other areas like social sciences. For both, new product development and design-to-value, the value identification is needed. In the SLR [42], mention value creation by examining the potential role of hydrogen exports.

Efforts from industry, universities and funding mechanisms are necessary in increase responsible R&D [67,96]. Aditiya and Aziz [90] mention different policies and strategies for 11 countries and hydrogen valleys. The diversity of stakeholder backgrounds can affect the outcomes of R&D projects [38].

Due to the close relationship between R&D and education, Aditiya and Aziz [90] propose two metrics to study R&D: (1) the human development index (aggregates indicators from the education dimension, living standard, earnings, and life expectancy level); (2) a research and development capacity indicator.

Although some authors from the SLR do not mention R&D in the analysed sections (title, abstract or keywords), there are contributions to the topic by Griffiths et al. [24], who centre their work on industry decarbonisation and list a set of elements to policy mechanisms relevant to R&D.

4.11. Responsibility

When talking about "responsibility" there is a connection between H_2 products and operations. Both have a social impact (responsibility) and should have a sustainable growth. This category is related to 29 % of the papers. Although the implementation status is still at a strategic stage, there are plans to accelerate the deployment, and industrial scale-up of hydrogen technologies and operations. Several subcategories were found.

For the first one, there is information linked to "implementation" that includes project plans, project management and infrastructure demonstration/deployment [25,43,66,101,102].

The second one applies to the "risk management" subcategory that includes reliability, financial and social risk assessment regarding the implementation. Operations' disruption and blockage of end-user practices are also part of risk management [35,63,65,78,89,100,103].

For the third subcategory, only two articles[5] from the sample explicitly discusses the "social life cycle assessment" (S-LCA) methodology with a focus on the sociological impact of alkaline water electrolysis by a quantitative analysis through PSILCA[6] [20,92]. S-LCA is done by systematising data (often subjective) and reporting the positive and negative social impacts in product lifecycles from cradle to gate. Guidelines for S-LCA were published in 2009 and 2021 [17,104] but have not yet resulted in a commonly accepted framework, unlike environmental LCA studies [20]. Since S-LCA includes social aspects, it is more relevant than the classic environmental LCA for this review. However, as discussed in Section 4.8, the carbon footprint is measured through the classic environmental LCA, and the impact on human activity can be analysed because carbon is monetized and paid by different organisations and stakeholders. However, in S-LCA there might be lack of information due to aggregation.

The fourth subcategory is "social responsibility" presented in Ref. [19] which consider the aspects of the environment; ethics, rights and obligations; and poverty and sustainable development. The concept of corporate social responsibility (CSR) could be used, but additional implementation and research are needed. CSR is generally defined as businesses' commitment and contribution (impact) to sustainable development [19]. Recent papers are connecting their discussions around the sustainability, social sustainability, and SDGs issues [21,27,67,92,96].

At an operational level, the working conditions are a topic of interest in Refs. [20,92] for an alkaline water electrolysis production plant.

4.12. Technological safety

In this category, risks related to technological safety are included; 22 % of the papers provided elements on the title, abstract or keywords to be part of this category. An additional check of the articles' content was needed due to the multiple meanings that can be attributed to the word "risk" [89,105]. Papers such as the one developed by Griffiths et al. [24], that discuss the importance of safety regulation could have also been included if stating any associated keyword on the search fields.

This category is explicitly labelled as "technological safety" and is associated with the practice of risk assessment as the effect of hazard and likelihood. It is often referred to along with infrastructure [77,89,106], and it is highlighted in previous sections that it has a relationship with acceptability and accessibility. Safety perception is an important factor in acceptability studies [26,52]. Opposition appears to be related to safety risks concerns [19,23,37]. Safety impacts can be evaluated in a quantitative and qualitative manner. Some examples of indices are: (1) the social health cost – when accidents at a chemical plant (e.g., an explosion) cause health risks to society [106], (2) fatalities, (3) property damage, and (4) health damage [46]. Finally, the risk of accidents could require that hydrogen facilities are located in specific areas [106].

5. Gaps and perspectives for future research

The research gaps are summarised in Table 3 to provide insightful identification of challenges. New thinking and research questions are listed for each pre-identified social aspect, and perspectives about the potential tools or theories are given.

5. Summary

Accessibility. The main challenge is the deployment of reliable products at an accessible price and the availability of infrastructure that is part of a sustainable and reliable HSC. But besides the fuel or equipment prices, how can the accessibility of hydrogen supply be measured in common terms for society? Further research is needed to develop specific measures for assessing the accessibility of hydrogen supply in terms of physical or economic accessibility. This includes exploring indicators that can capture the share of the population excluded from accessing hydrogen and incorporating societal, strategic, and operational performance objectives. The term "sustainability" is key in the expected deployment of HSCs, and this guides the new modelling efforts to include sustainability criteria in any plans to deploy hydrogen infrastructure. These criteria should be presented to society to allow comparison with other energy supply chain options and should be aligned with large frameworks such as SDGs. In the coming decades, it is expected that there will be some antagonism between the sustainability criteria (e.g., cost and environmental impact) and the current efforts for applying multiobjective optimisation [49] continue to be a plausible option, but is this the only option to do it? There is a need to avoid only employing top-down approaches through the inclusion of polycentric approaches mixing scales and mixing actors [8]. Additionally, studying the impact of critical and scarce materials on the sustainability, reliability, and resilience of the hydrogen supply chain is important. Understanding investor motivation and incorporating lessons learned from pilot projects can also provide valuable insights into accessibility options, constraints, and risks [107–109]. Finally, accessibility is connected to many other social aspects and further research is needed to study the relationships.

Information. There is a challenge to have accurate, reliable, and timely information in the era of the digital economy to operationalise the hydrogen economy. Context plays an important role in the use of

[5] [112] also use S-LCA and published their results in the proceedings of Energy Procedia.

[6] Product Social Impact Life Cycle Assessment database.

Table 3
Gaps and perspectives for future research on social aspects related to the hydrogen economy.

Social aspect	Gap or challenge	Research questions (RQs)	Potential theoretical lens
Accessibility	Ensure reliable and sustainable access to hydrogen products and technology	RQ1A. How can the availability of hydrogen supply be measured in common terms for society? RQ1B. How can sustainability be ensured when providing hydrogen to citizens? RQ1C. What are the alternatives for H_2 supply chain design to ensure a reliable (financially and technologically) and resilient operation? RQ1D. What is the role of critical materials availability in ensuring access to H_2 markets and technology? RQ1E. What is the impact of the HSC deployment as understood in the SDGs? RQ1F. How can investors be motivated to invest in hydrogen technology to make it available to society?	Supply Chain Management (strategic, tactical and operational) Operations research and operations management Socio-technical systems design Sustainable supply chain design and SDGs Technological Innovation System approach Multiobjective optimisation Multiperiod and multidimensional analysis Multi-criteria decision making Context analysis (e.g. geographic information system) Reliability and resilience assessment
Information	Accurate, reliable, and timely information in the era of the digital economy to operationalise the hydrogen economy	RQ2A. In which ways are digital tools and social media being used to spread information about H_2?" RQ2B. What are the value elements related to H_2 markets that should be disseminated to society? RQ2C. Usability of labelling of products produced by H_2 technologies? RQ2D. At what level will information sharing be available for different stakeholders of the HSC? RQ2E. How can the accuracy and reliability of hydrogen information be ensured in the new AI era? RQ2F. How can training and education programs be developed, aligned and regulated? RQ2G. What is the way how digital tools and social media are used to spread information about H_2?	Digital Economy and Society Index (DESI) Enterprise resource planning, Collaborative commerce (C-commerce), Transactions costs theory Traceability and Transparency Multidimensional Labelling
H_2 markets	Value definition, and H_2 competitiveness	RQ3A. What is the value of hydrogen? RQ3B. What is the strategy for hydrogen to stand in front of its competitors in different markets? RQ3C. What are useful marketing strategies that can be used to increase the hydrogen share? RQ3D. How will hydrogen be differentiated (H_2 colour, emissions, cost, etc.)? RQ3E. How can current consumers of grey hydrogen switch to green hydrogen? RQ3F. What is the role of different organisation sizes in the supply of H_2 markets? RQ3G. How can H_2 stakeholders increase productivity and efficiency?	Value definition Market research Strategic Niche Management Multi-criteria decision making Social cost-benefit analysis Operations management Product life cycle assessment Context, policy and regulation Circularity
Acceptability	Acceptability measurement, and influence	RQ4A. In H_2 acceptability assessment, how are the validity and reliability of the questionnaires ensured? RQ4B. What is the interrelation of H_2 acceptability with other social situations (war, pandemics) or aspects? RQ4C. How should the different stakeholders have been approached for assessing H_2 acceptability? RQ4D. How are the H_2 acceptability measures being reported? What is the best way to do it? RQ4E. How will the different hydrogen colours affect its image and usage? RQ4F. Is the "risk" aspect fairly evaluated in acceptability studies? Is it safety risk, economic risk, etc.?	Qualitative research Social-psychology research Market research Unified Theory of acceptance and usage of technology Socio-Technical design Context analysis
Policies and regulations	Fully developed policies, standards, and regulations	RQ5A. What is the impact of policies and regulation in the deployment of the hydrogen economy?	Transition Management Planetary boundaries framework Policy and regulation development Standardisation
Socio-political factors	Understand socio-political factors that are related to the hydrogen economy	RQ6A. What are the missing socio-political aspects that play an important role in the hydrogen economy? RQ6B. How can the impact on social well-being be measured when different fuels are competing? RQ6C. What is the impact of the political discourse in the hydrogen economy deployment?	Energy independence or security Power and influence Quality of life and social wellbeing Energy geopolitics Patriotism, culture, and progress Democracy and freedom Equity, fairness and solidarity Diversity and equal opportunities
Stakeholders	Collaboration and leadership	RQ7A. Can stakeholders' collaboration be a realistic approach to supplying hydrogen to society? RQ7B. How can the stakeholders affect the decision-making within the hydrogen supply chain? Which roles are more significant? RQ7C. What types of common tools or protocol could be useful to	Social representations theory Role theory Stakeholder theory Relationship marketing Game theory

(continued on next page)

Table 3 (*continued*)

Social aspect	Gap or challenge	Research questions (RQs)	Potential theoretical lens
		aiding communication and decision making of H_2 stakeholders with heterogeneous profiles?	
Externalities	Assessment of all costs and benefits of H_2 economy beyond individual/private level	RQ8A. Are all costs and benefits regarding the H_2-economy comprehensively identified and correctly monetized?	SCBA Levelized cost of hydrogen
Socio-economic factors	Understand socio-economic factors that related to the hydrogen economy	RQ9A. What are the recommended socio-economic metrics that should be reported in hydrogen projects? RQ9B. How the tools of environmental economics like taxes, subsidies and tradable emission permits can be adjusted to or incorporated in H_2 economy?	Socioeconomics; Environmental economics
R&D	Impact of R&D initiatives	RQ10A. What is the impact of R&D in the decision-making for the implementation and deployment of hydrogen technologies? RQ10B. How effective are the funding strategies in the hydrogen economy implementation?	Sociology of innovation Responsible innovation Project and risk management
Responsibility	Social sustainability concept, and S-LCA	RQ11A. What is the best way to evaluate the social sustainability of H_2 initiatives? RQ11B. How can the SDGs framework be used to track the social responsibility of hydrogen projects? RQ11C. How can the managers evaluate and incorporate metrics for energy impact on the operations performance by clearly comparing the impact of fuels, not just reporting economic or environmental impacts, but also in terms of social sustainability? RQ11D. How can CSR and other social responsibility standards be connected to the migration of fossil fuels to hydrogen by highlighting societal benefits? RQ11E. What is needed to fulfil the S-LCA guidelines agreement?	Social sustainability (GRI aspects) Operations strategy and objectives definition Sustainable Development Goals Social Life Cycle Assessment Circularity
Technological safety	Supply chain reliability	RQ12A. What is the expected technological reliability of hydrogen supply chains when different geographical conditions and technology types are considered?	Risk management Technological reliability assessment

communication tools to spread and use information. Usability of labelling products produced by H_2 technologies is an important future research question and labelling products is an important tool for this aspect [110]. Digitalisation and IoT can improve social awareness [16, 111] but there is a need to search for how public awareness of H_2 products and technology can affect their perception and acceptability. This question can be connected to the existent discourse. The amount and type, of information shared will have an influence on acceptability. To allow society to make informed decisions, it is critical not only to share the benefits of switching to hydrogen, but also its limitations and risks [105,112] for different paths (e.g., blue or green H_2). It is highlighted that there is a close relationship between two of the social aspects: "information" and "acceptability". For this reason, additional research about the public awareness of hydrogen and related attitudes/acceptability is expected in the following years. The effect caused by informing people in public participation could be investigated further [8]. In terms of information sharing at the organisational level, there is uncertainty about the type of communication and information tools that will be used (e.g., collaborative commerce, c-commerce). Many initiatives are expected for information related to training and education (e.g., employees' educational level, training, education, and upskilling). New educational programs are needed to explain the different technologies in the hydrogen economy, and there is also a need to certify and prepare technicians, experts, teachers, and professors. Learning measurement will be crucial from the practical, and financial perspectives.

H_2 markets. The lack of a definition of the value of H_2 products is the main gap for this aspect. Although the environmental and flexibility benefits are often presented, there is a need for specific value definitions of different type of hydrogen products for market deployment. More research on hydrogen products competitiveness is also needed. The clarity in the definition of the value of hydrogen will not only allow the hydrogen producers to define the price, but it will also enable them to inform the customers about the benefits included for different hydrogen products (more than just H_2 colours and emissions). This topic is critical for current hydrogen users or producers that must switch from grey to blue or green hydrogen in the following years.

Acceptability. Although there are more and more studies using questionnaires to measure H_2 acceptability, there is a need to report statistical data to display the validity and reliability of the questionnaires. The development of questionnaires and instruments for measuring acceptability is not standardised, but some efforts can be put forth to resolve this issue. Moreover, assessment of stakeholders' acceptability, expectations, and trust can be further analysed [108,109], and as a perspective, the attitudes of stakeholders-users can be connected to market analyses [113]. As previously explained, the influence and relationship between "acceptability" and "information" can be explored. Some examples that can affect this aspect are the value of hydrogen, safety, war, pandemics, impact on public health, employment and training opportunities [51]. Customer satisfaction with demonstration projects [114], and field experiences [115] could be shared. Furthermore, exploration of the acceptability of operations and their public image based on energy consumption could also be treated [16]. Finally, there is a need to clearly define risk during surveys to avoid confusion [risk management, safety risk, etc.] [105].

Externalities. To achieve the economic competitiveness of H_2 markets, it is paramount to design hydrogen supply chains including externalities through a SCBA, and other sustainability metrics. The effect caused by carbon taxes can be more deeply evaluated by including recent programs such as Fit-for-55 [116]. However, it is highlighted that data about externalities can be difficult to find or aggregated.

Policies and regulations. The key challenge for this category is to have fully developed policies, standards, and regulations. Regulatory and standardization instruments are perhaps the essential means of driving rapid hydrogen utilisation [68], but once these policies and regulations are in place, a question that might arise is: what are the impacts of policies and regulations in the deployment of the hydrogen economy?

Stakeholders. The key challenge identified is "collaboration and leadership" for the HSC deployment. Even if the relevance of "collaboration" is usually highlighted in meetings and presentations related to the hydrogen economy, there is a scientific research gap in the study of stakeholder's collaboration. It can be discussed if cooperation is possible in a competitive context, and if so, at what level would this be a reality. For this aspect, it is crucial to employ approaches that increase understanding of stakeholder dialogue [117]. The stakeholder's analysis is not a trivial task because there is heterogeneity and different levels of influence related to the roles of stakeholders [97] which might affect the views and relationships in the HSC. Another missing topic is the cultural dimension, which can also be included as part of stakeholder analysis because ideology and culture can influence the perceptions and behaviours of people [105].

Socio-political factors. Our SLR displays a short list of socio-political factors, and there is a need to identify the key additional social-political factors related to hydrogen economy and energy transition. We suggest including broad social categories from approaches like those used in the SDGs [118] or SFI frameworks [119] to better represent the complexity of social systems. Some of the following aspects can be analysed in a more profound way. First, energy independence or energy security, which could incorporate the humanitarian and political dimensions of international changes (e.g., pandemics) and geopolitical risks (e.g., war). At a global level, social relations should take into account larger categories such as energy poverty and energy solidarity [79,88,120]. The relationship of the introduction of hydrogen products could also be studied through its effects on quality of life (life expectancy index, infant mortality index or adult literacy rate) and well-being (e.g., Well-Being Index; Personal, Subjective, and Social Wellbeing [121–124], and "happiness per capita" [125]. Alternative socio-political aspects to be explored are: energy geopolitics; patriotism and progress [12,126]; democracy and freedom [112,126]; decent life [112]; equity/fairness/solidarity; diversity and equal opportunities (gender, rights of indigenous people); and the analysis of political themes and rhetorical visions (e.g., independence, patriotism, progress, democratisation) [126]. Cultural and ethical aspects should also be included in future analyses [127].

Socio-economic factors. Besides "jobs and employment" metrics, what are the most appropriate socio-economic figures that should be reported in hydrogen projects? How the tools of environmental economics like taxes, subsidies, and tradable emission permits - developed for managing externalities - can be adjusted to or incorporated in H_2 economy? [128].

R&D. Two classical research questions are related to this category: (1) what is the impact of R&D in the decision-making for the implementation and deployment of hydrogen technologies? and (2) how effective are the funding strategies in the hydrogen economy implementation? Some measurement examples are the share of scientific publication, patents, and facilities. From this social aspect, "information" can be impacted because technological outcomes will change the content of courses and trainings. This point is also connected to "stakeholders".

Responsibility. As explained in the introduction, the term "social sustainability" can be analysed from different perspectives. From the point of view of different operations, specific metrics could be applied. For example, gender equality for achieving SDG 5 [10,14], corporate social responsibility[7] [16,19,22,75,129], etc. However, there is a need for a structured framework for social sustainability such as the one used in "operations management" that uses four social aspects proposed by the GRI (Human Rights, Labour Conditions, Society and Product Responsibility) [14–16]. From this perspective no papers were found, so further research can be developed. Efforts are also needed to have scientific agreement on the applicability of S-LCA to HSCs, which seems a promising tool due to its similar structure and methodology to the environmental LCA.

Technological safety. Many studies are taking place around the technological safety of hydrogen technology (e.g., safety risk index [130], FAST and HAZOP methods [131], and Quantitative Risk Assessment [132]. All the methodologies face the same challenge of quantifying the risk due to technological maturation. There is a need for new research focusing on safety risk assessment, and HSC reliability to allow the identification of safe working conditions and operation of hydrogen technologies to implement preventive actions that can be easily shared with the users.

5.1. Implications and significance of the findings

The potential impact of the findings presented in this work are various and can be useful to a scientific community, industry, policy makers, consultants, and international agencies. Social aspects affect all the aspects in the communities and are closely linked to economy, energy use, and businesses. Have potential impact on local, regional, and international development, climate change and energy transition. To determine if hydrogen is a competitive option, the scenarios, models, and studies should include relevant social aspects. The limited inclusion of a single social index (e.g., "job creation", "risk index") in current models trying to have a sustainability perspective is not enough. Future works can be better structured by using the proposed categorisation as a reference to guide a holistic view and propose new contributions. As presented in Table 3, several research areas require development. Contributions from multidisciplinary teams can have a positive impact to align efforts and accelerate the development of requirements (public participation, debate, cooperation, products testing and development, safety, acceptability assessment, policy, and regulation, resilience, and reliability, etc.) prior technological scale-up, and implementation. It is important to keep in mind the social context, the socio-political and socio-economic dynamics because they have an implication in the strategies around the hydrogen economy. In this sense, public participation is needed to guarantee a fair and transparent evaluation of hydrogen vs other fuels. Stakeholders and potential final users need to understand clearly what the value of hydrogen is for society (information access is a critical aspect). On the other hand, there is a need for agreement from the scientific community around the use S-LCA and "social sustainability" frameworks widely; for organisations it might be necessary to count with specific frameworks connected to the SDGs. Finally, it is key to understand how to integrate hydrogen in the social practices considering cultural issues making it possible to develop the hydrogen markets and to implement projects in a smooth manner to make accessible hydrogen products to society.

6. Conclusion

This article is an effort to summarise social science, sustainability, and engineering viewpoints on H_2 technologies in society. Identification, categorisation, and analysis of the social aspects were carried out using a domain-based systematic literature review (SLR) that combined both bibliometric and structured approaches by searching for two main keywords in article titles: "hydrogen" and "social". In this paper, the social aspects of the hydrogen economy were defined as all aspects that concern people and their interactions and relationships within a hydrogen system. A total of 65 papers were obtained from Web of Science and Scopus that fit the proposed research profile.

With an initial search it was found that several papers use the term "social" and "society" as generic terms and do not address specific social aspects. Going deeper into the analysis, the bibliometric and structured reviews allowed the identification and definition of twelve main social aspects. The categories were ranked based on the occurrence of terms. The identified social aspects are indeed generic and could be applied to any new technology but in this review, they were only connected to hydrogen-related research. The dominant categories are accessibility, information, H_2 markets, acceptability and policies & regulation. Other categories are socio-political factors, stakeholders, externalities, socio-economic factors, and research & development. The two social aspects with the lowest occurrence – but still important – are: responsibility and technological safety. Some papers include two or more of the above-mentioned categories. As a theoretical contribution, each category

[7] "to create favorable conditions [for] sustainable growth, responsible business behavior and durable employment generation in the medium and long term" (European Commission, 2011).

presented in this paper was synthetised, gaps were detected, and perspectives about future research were also shared.

Although several gaps and perspectives have been identified, four of them can be highlighted: (1) the definition of H_2 value is missing; (2) relatively few papers deal with the so-called "socio-political" dimension, and important aspects such as geopolitics, energy independence, equity, fairness, solidarity, and human wellbeing are only vaguely explored; (3) no articles treat the topic of "social sustainability" as used in the field of supply chain management; (4) surprisingly, "technological safety" is one of the less mentioned social aspects while this topic is related to many other categories (i.e., acceptability and accessibility), and is a precondition to ensure a sustainable and reliable implementation of hydrogen technologies. In addition, cultural and ethical aspects, interconnections, and correlation of the social aspects are missing. More research about social practices is needed to understand how H_2 would improve or affect the life of people.

Promising frameworks or tools to incorporate social aspects in formal studies are: (a) the social-LCA (listed in the "responsibility" aspect) which provides useful guidelines and can analyse the social impact for products at different stages of the hydrogen supply chain; however, scientific agreement on its applicability is needed to use this approach; and (b) social cost-benefit analysis can be a useful approach if more "externalities" could be included in models to compare products and/or technologies.

As with all types of literature review, the present study has some limitations. To create clear boundaries and transparency for the review, predominantly peer-reviewed scientific articles, and reviews in English from two internationally recognized databases, were used. The selection of the keywords in the search sections may be a limitation of our approach. Based on the authors' experience, some papers that indeed include social aspects cannot be identified by searching for the term "social" in the title, abstract or keywords. For this reason, better keywording of papers is recommended to help researchers from different fields find them in a more systematic way and increase their visibility. A group of four researchers from different disciplines worked on revisions to reduce bias, as an effort to improve and balance the review approach; however, as a literature review, the analysis represents the authors' perspective. In this sense, a subjective analysis of titles, abstracts, and keywords of the selected documents has been conducted to ensure that only relevant publications have been included and to categorize the content. Some of the different categories are inherently interrelated (e.g., information, acceptability, etc.), and could be formally analysed to identify their correlation. Despite these constraints, this review article attempts to generate a reliable identification of the current status and gaps in research related to the social aspects in the hydrogen economy by following a rigorous methodology and providing all the information to the reader.

From a practical point of view, including researchers from the fields of engineering, economics and sociology was considered of great importance, allowing us to identify theoretical approaches, and insights that could improve research on the social aspects associated with hydrogen. Multidisciplinary approaches have the potential to better integrate the social aspects into the hydrogen models, and to improve the understanding of the potential social implications of hydrogen alternatives.

Funding

This work was supported by the Corvinus Institute for Advanced Studies [grant number CIAS-44/2021].

Declaration of competing interest

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

Acknowledgements

We would like to thank Grzegorz Leszczyński and Péter Balogh for the helpful comments and discussions. We also acknowledge Simon Milton and Aaron Honish for proofreading.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2023.10.043.

References

[1] OECD. Making the Green Recovery work for jobs, income and growth 2. 2020.
[2] European Commission. Horizon 2020:2020.
[3] European Commission. Communication from the commission to the European parliament, the European council, the council. In: The European economic and social committee and the committee of the regions. REPowerEU Plan. EUR-Lex; 2022. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483 (accessed June 26, 2022).
[4] Azzaro-Pantel C. Hydrogen supply chains. 1.ª ed 2018.
[5] IEA. The future of hydrogen. 2019.
[6] IRENA. Hydrogen: a renewable energy perspective. 2019. Japan.
[7] IEA. Global hydrogen review. 2021. p. 2021.
[8] Krumm A, Süsser D, Blechinger P. Modelling social aspects of the energy transition: what is the current representation of social factors in energy models? Energy 2022;239:121706. https://doi.org/10.1016/J.ENERGY.2021.121706.
[9] Hanusch F, Schad M. Hydrogen research: technology first, society second? GAIA - Ecol Perspect Sci Soc 2021;30:82–6. https://doi.org/10.14512/gaia.30.2.5.
[10] United Nations. SDG indicators — SDG indicators. United Nations; 2020. https://unstats.un.org/sdgs/indicators/indicators-list/ (accessed Sep 8, 2021).
[11] Castor J, Bacha K, Fuso Nerini F. SDGs in action: a novel framework for assessing energy projects against the sustainable development goals. Energy Res Social Sci 2020;68:101556. https://doi.org/10.1016/J.ERSS.2020.101556.
[12] Szántó ZO, Mueller JD. Social futuring, modern and ancient. 2022. p. 1–30. https://doi.org/10.1080/02604027.2022.2059305.
[13] Harris JM, Goodwin NR. Introduction. En: press I. In: A Surv, editor. Sustain. Dev. Soc. Econ. Washington, DC: Dimens; 2001.
[14] Popovic T, Barbosa-Póvoa A, Kraslawski A, Carvalho A. Quantitative indicators for social sustainability assessment of supply chains. J Clean Prod 2018;180:748–68. https://doi.org/10.1016/j.jclepro.2018.01.142.
[15] GRI. GRI Standards. GRI s. f. 2021. https://www.globalreporting.org/ (accessed June 8, 2022).
[16] Bubicz ME, Barbosa-Póvoa APFD, Carvalho A. Incorporating social aspects in sustainable supply chains: trends and future directions. J Clean Prod 2019;237:117500. https://doi.org/10.1016/j.jclepro.2019.06.331.
[17] UNEP, Social LC Alliance. Methodological sheets for subcategories in social life cycle assessment (S-LCA) 2021. 2021.
[18] Assefa G, Frostell B. Social sustainability and social acceptance in technology assessment: a case study of energy technologies. Technol Soc 2007;29:63–78. https://doi.org/10.1016/j.techsoc.2006.10.007.
[19] Ingaldi M, Klimecka-Tatar D. People's attitude to energy from hydrogen—from the point of view of modern energy technologies and social responsibility. Energies 2020;13:6495. https://doi.org/10.3390/en13246495.
[20] Werker J, Wulf C, Zapp P. Working conditions in hydrogen production: a social life cycle assessment. J Ind Ecol 2019;23:1052–61. https://doi.org/10.1111/jiec.12840.
[21] Blohm M, Dettner F. Green hydrogen production: integrating environmental and social criteria to ensure sustainability. Smart Energy 2023;11:100112. https://doi.org/10.1016/J.SEGY.2023.100112.
[22] Klassen RD, Vereecke A. Social issues in supply chains: capabilities link responsibility, risk (opportunity), and performance. Int J Prod Econ 2012;140:103–15. https://doi.org/10.1016/J.IJPE.2012.01.021.
[23] Wijayasekera SC, Hewage K, Siddiqui O, Hettiaratchi P, Sadiq R. Waste-to-hydrogen technologies: a critical review of techno-economic and socio-environmental sustainability. Int J Hydrogen Energy 2022;47:5842–70. https://doi.org/10.1016/j.ijhydene.2021.11.226.
[24] Griffiths S, Sovacool BK, Kim J, Bazilian M, Uratani JM. Industrial decarbonization via hydrogen: a critical and systematic review of developments, socio-technical systems and policy options. Energy Res Social Sci 2021;80. https://doi.org/10.1016/j.erss.2021.102208.
[25] Emodi NV, Lovell H, Levitt C, Franklin E. A systematic literature review of societal acceptance and stakeholders' perception of hydrogen technologies. Int J Hydrogen Energy 2021;46:30669–97. https://doi.org/10.1016/j.ijhydene.2021.06.212.
[26] Vallejos-Romero A, Cordoves-Sánchez M, Cisternas C, Sáez-Ardura F, Rodríguez I, Aledo A, et al. Green hydrogen and social sciences: issues, problems, and future challenges. Sustain Times 2023;15. https://doi.org/10.3390/SU15010303.
[27] Sharma GD, Verma M, Taheri B, Chopra R, Parihar JS. Socio-economic aspects of hydrogen energy: an integrative review. Technol Forecast Soc Change 2023;192:122574. https://doi.org/10.1016/J.TECHFORE.2023.122574.

[28] Paul J, Criado AR. The art of writing literature review: what do we know and what do we need to know? Int Bus Rev 2020;29:101717. https://doi.org/10.1016/J.IBUSREV.2020.101717.
[29] Kar SK, Harichandan S, Roy B. Bibliometric analysis of the research on hydrogen economy: an analysis of current findings and roadmap ahead. Int J Hydrogen Energy 2022;47:10803–24. https://doi.org/10.1016/J.IJHYDENE.2022.01.137.
[30] Catumba BD, Sales MB, Borges PT, Ribeiro Filho MN, Lopes AAS, Sousa Rios MA de, et al. Sustainability and challenges in hydrogen production: an advanced bibliometric analysis. Int J Hydrogen Energy 2023;48:7975–92. https://doi.org/10.1016/j.ijhydene.2022.11.215.
[31] Harichandan S, Kar SK, Rai PK. A systematic and critical review of green hydrogen economy in India. Int J Hydrogen Energy 2023. https://doi.org/10.1016/J.IJHYDENE.2023.04.316.
[32] Harichandan S, Kar SK, Bansal R, Mishra SK, Balathanigaimani MS, Dash M. Energy transition research: a bibliometric mapping of current findings and direction for future research. Clean Prod Lett 2022;3:100026. https://doi.org/10.1016/J.CLPL.2022.100026.
[33] van Eck NJ, Waltman L. VOSviewer - visualizing scientific landscapes. 2009. https://www.vosviewer.com/. [Accessed 18 June 2022].
[34] Arsad AZ, Hannan MA, Al-Shetwi AQ, Mansur M, Muttaqi KM, Dong ZY, et al. Hydrogen energy storage integrated hybrid renewable energy systems: a review analysis for future research directions. Int J Hydrogen Energy 2022;47:17285–312. https://doi.org/10.1016/J.IJHYDENE.2022.03.208.
[35] Apostolou D, Welcher SN. Prospects of the hydrogen-based mobility in the private vehicle market. A social perspective in Denmark. Int J Hydrogen Energy 2021;46:6885–900. https://doi.org/10.1016/j.ijhydene.2020.11.167.
[36] Ochoa Robles J, Azzaro-Pantel C, Martinez Garcia G, Aguilar Lasserre A. Social cost-benefit assessment as a post-optimal analysis for hydrogen supply chain design and deployment: application to Occitania (France). Sustain Prod Consum 2020;24:105–20. https://doi.org/10.1016/j.spc.2020.06.010.
[37] O'Garra T, Mourato S, Pearson P. Investigating attitudes to hydrogen refuelling facilities and the social cost to local residents. Energy Pol 2008;36:2074–85. https://doi.org/10.1016/j.enpol.2008.02.026.
[38] Upham P, Dütschke E, Schneider U, Oltra C, Sala R, Lores M, et al. Agency and structure in a sociotechnical transition: hydrogen fuel cells, conjunctural knowledge and structuration in Europe. Energy Res Social Sci 2018;37:163–74. https://doi.org/10.1016/j.erss.2017.09.040.
[39] Oliveira Carlos de Morais D, Carlos Barbieri J. Social performance measurement for sustainable supply chain management. Prod. Oper. Manag. Soc. (POMS). 2016;27. Orlando.
[40] Berrada A, Laasmi MA. Technical-economic and socio-political assessment of hydrogen production from solar energy. J Energy Storage 2021;44:103448. https://doi.org/10.1016/j.est.2021.103448.
[41] Chu H, He J, Yang Y, Huang Y, Wang S, Wu Y. Economic-environmental-social benefits assessment of wind power hydrogen production project based on cloud-MULTIMOORA approach. Sustain Times 2022;14:9118. https://doi.org/10.3390/SU14159118. 9118 2022;14.
[42] Espegren K, Damman S, Pisciella P, Graabak I, Tomasgard A. The role of hydrogen in the transition from a petroleum economy to a low-carbon society. Int J Hydrogen Energy 2021;46:23125–38. https://doi.org/10.1016/j.ijhydene.2021.04.143.
[43] Rezaei M, Salimi M, Momeni M, Mostafaeipour A. Investigation of the socio-economic feasibility of installing wind turbines to produce hydrogen: case study. Int J Hydrogen Energy 2018;43:23135–47. https://doi.org/10.1016/j.ijhydene.2018.10.184.
[44] Trattner A, Klell M, Radner F. Sustainable hydrogen society – vision, findings and development of a hydrogen economy using the example of Austria. Int J Hydrogen Energy 2022;47:2059–79. https://doi.org/10.1016/j.ijhydene.2021.10.166.
[45] Chapman A, Itaoka K, Farabi-Asl H, Fujii Y, Nakahara M. Societal penetration of hydrogen into the future energy system: impacts of policy, technology and carbon targets. Int J Hydrogen Energy 2020;45:3883–98. https://doi.org/10.1016/j.ijhydene.2019.12.112.
[46] Chapman AJ, Fraser T, Itaoka K. Hydrogen import pathway comparison framework incorporating cost and social preference: case studies from Australia to Japan. Int J Energy Res 2017;41:2374–91. https://doi.org/10.1002/er.3807.
[47] Glanz S, Schönauer A-L. Towards a low-carbon society via hydrogen and carbon capture and storage: social acceptance from a stakeholder perspective. J Sustain Dev Energy, Water Environ Syst 2021;9. https://doi.org/10.13044/j.sdewes.d8.0322. 0-0.
[48] Nurdiawati A, Urban F. Decarbonising the refinery sector: a socio-technical analysis of advanced biofuels, green hydrogen and carbon capture and storage developments in Sweden. Energy Res Social Sci 2022;84:102358. https://doi.org/10.1016/j.erss.2021.102358.
[49] De-León Almaraz S, Rácz V, Azzaro-Pantel C, Szántó ZO. Multiobjective and social cost-benefit optimisation for a sustainable hydrogen supply chain: application to Hungary. Appl Energy 2022;325:119882. https://doi.org/10.1016/J.APENERGY.2022.119882.
[50] Gordon JA, Balta-Ozkan N, Nabavi SA. Socio-technical barriers to domestic hydrogen futures: repurposing pipelines, policies, and public perceptions. Appl Energy 2023;336:120850. https://doi.org/10.1016/j.apenergy.2023.120850.
[51] Acar C, Dincer I. Review and evaluation of hydrogen production options for better environment. J Clean Prod 2019;218:835–49. https://doi.org/10.1016/j.jclepro.2019.02.046.
[52] Lozano LL, Bharadwaj B, de Sales A, Kambo A, Ashworth P. Societal acceptance of hydrogen for domestic and export applications in Australia. Int J Hydrogen Energy 2022;47:28806–18. https://doi.org/10.1016/J.IJHYDENE.2022.06.209.
[53] Sun Y, Ogden J, Delucchi M. Societal lifetime cost of hydrogen fuel cell vehicles. Int J Hydrogen Energy 2010;35:11932–46. https://doi.org/10.1016/j.ijhydene.2010.08.044.
[54] Cantuarias-Villessuzanne C, Weinberger B, Roses L, Vignes A, Brignon J-M. Social cost-benefit analysis of hydrogen mobility in Europe. Int J Hydrogen Energy 2016;41:19304–11. https://doi.org/10.1016/j.ijhydene.2016.07.213.
[55] Kaneberg E, Rico M, Hertz S, Jensen L-M, Sandoval-Pineda JM, Gonzalez Huerta R. Hydrogen technology for supply chain sustainability: the Mexican transportation impacts on society. Int J Hydrogen Energy 2022. https://doi.org/10.1016/j.ijhydene.2022.03.081.
[56] Lin R-H, Zhao Y-Y, Wu B-D. Toward a hydrogen society: hydrogen and smart grid integration. Int J Hydrogen Energy 2020;45:20164–75. https://doi.org/10.1016/j.ijhydene.2020.01.047.
[57] McDowall W, Eames M. Towards a sustainable hydrogen economy: a multi-criteria sustainability appraisal of competing hydrogen futures. Int J Hydrogen Energy 2007;32:4611–26. https://doi.org/10.1016/j.ijhydene.2007.06.020.
[58] Mourik R, De Groot A, Jeeninga H. Challenges in the transition toward a hydrogen-based society: an in-depth study to assess the potential of a transition to a hydrogen-based energy supply in Europe. Clean Air Int J Energy a Clean Environ 2006;7:239–54. https://doi.org/10.1615/InterJEnerCleanEnv.v7.i3.40.
[59] Rahil A, Gammon R, Brown N, Udie J, Mazhar MU. Potential economic benefits of carbon dioxide (CO2) reduction due to renewable energy and electrolytic hydrogen fuel deployment under current and long term forecasting of the Social Carbon Cost (SCC). Energy Rep 2019;5:602–18. https://doi.org/10.1016/j.egyr.2019.05.003.
[60] Zhou Y, Li R, Lv Z, Liu J, Zhou H, Xu C. Green hydrogen: a promising way to the carbon-free society. Chin J Chem Eng 2022;43:2–13. https://doi.org/10.1016/j.cjche.2022.02.001.
[61] Di Mario F, Mattucci A, Iacobazzi A, Infusino R. Socioeconomic aspects of hydrogen economy development. Clean Air Int J Energy a Clean Environ 2006;7:303–26. https://doi.org/10.1615/InterJEnerCleanEnv.v7.i4.10.
[62] Yap J, McLellan B. Evaluating the attitudes of Japanese society towards the hydrogen economy: a comparative study of recent and past community surveys. Int J Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.05.174.
[63] Hultman M. Back to the future: the dream of a perpetuum mobile in the atomic society and the hydrogen economy. Futures 2009;41:226–33. https://doi.org/10.1016/j.futures.2008.09.006.
[64] McDowall W. Exploring possible transition pathways for hydrogen energy: a hybrid approach using socio-technical scenarios and energy system modelling. Futures 2014;63:1–14. https://doi.org/10.1016/j.futures.2014.07.004.
[65] Schnuelle C, Wassermann T, Stuehrmann T. Mind the gap—a socio-economic analysis on price developments of green hydrogen, synthetic fuels, and conventional energy carriers in Germany. Energies 2022;15:3541. https://doi.org/10.3390/en15103541.
[66] Park S. Iceland's hydrogen energy policy development (1998–2007) from a sociotechnical experiment viewpoint. Int J Hydrogen Energy 2011;36:10443–54. https://doi.org/10.1016/j.ijhydene.2011.06.031.
[67] Haussermann JJ, Maier MJ, Kirsch TC, Kaiser S, Schraudner M. Social acceptance of green hydrogen in Germany: building trust through responsible innovation. Energy Sustain Soc 2023;13:22. https://doi.org/10.1186/s13705-023-00394-4.
[68] Griffiths S, Sovacool BK, Kim J, Bazilian M, Uratani JM. Industrial decarbonization via hydrogen: a critical and systematic review of developments, socio-technical systems and policy options. Energy Res Social Sci 2021;80:102208. https://doi.org/10.1016/j.erss.2021.102208.
[69] Drożdż W, Elżanowski F, Dowejko J, Brożyński B. Hydrogen technology on the polish electromobility market. Legal, economic, and social aspects. Energies 2021;14:2357. https://doi.org/10.3390/en14092357.
[70] Iribarren D, Martín-Gamboa M, Manzano J, Dufour J. Assessing the social acceptance of hydrogen for transportation in Spain: an unintentional focus on target population for a potential hydrogen economy. Int J Hydrogen Energy 2016;41:5203–8. https://doi.org/10.1016/j.ijhydene.2016.01.139.
[71] Difiglio C, Gielen D. Hydrogen and transportation: alternative scenarios. Mitig Adapt Strategies Glob Change 2007;12:387–405. https://doi.org/10.1007/s11027-006-9074-1.
[72] Lin Z, Dong J, Greene DL. Hydrogen vehicles: impacts of DOE technical targets on market acceptance and societal benefits. Int J Hydrogen Energy 2013;38:7973–85. https://doi.org/10.1016/j.ijhydene.2013.04.120.
[73] Dissanayake PD, Sonne C, Cho WC, Kim CH, Ok YS. South Korea's big move to hydrogen society. Cogent Environ Sci 2020;6. https://doi.org/10.1080/23311843.2020.1856459.
[74] Hienuki S, Hirayama M, Hirayama Y, Kamada H, Kasai N, Shibutani T, et al. Public acceptance for the implementation of hydrogen self-refueling stations. Int J Hydrogen Energy 2021;46:35739–49. https://doi.org/10.1016/J.IJHYDENE.2021.08.115.
[75] Huijts N, van Wee B. The evaluation of hydrogen fuel stations by citizens: the interrelated effects of socio-demographic, spatial and psychological variables. Int J Hydrogen Energy 2015;40:10367–81. https://doi.org/10.1016/j.ijhydene.2015.06.131.
[76] You C, Kwon H, Kim J. Economic, environmental, and social impacts of the hydrogen supply system combining wind power and natural gas. Int J Hydrogen Energy 2020;45:24159–73. https://doi.org/10.1016/j.ijhydene.2020.06.095.
[77] Moonis M, Wilday AJ, Wardman MJ. Semi-quantitative risk assessment of commercial scale supply chain of hydrogen fuel and implications for industry and

society. Process Saf Environ Protect 2010;88:97–108. https://doi.org/10.1016/j.psep.2009.11.006.

[78] Scott M, Powells G. Sensing hydrogen transitions in homes through social practices: cooking, heating, and the decomposition of demand. Int J Hydrogen Energy 2020;45:3870–82. https://doi.org/10.1016/j.ijhydene.2019.12.025.

[79] Scott M, Powells G. Towards a new social science research agenda for hydrogen transitions: social practices, energy justice, and place attachment. Energy Res Social Sci 2020;61:101346. https://doi.org/10.1016/j.erss.2019.101346.

[80] Chen M, Zhang W-H. Purchase intention for hydrogen automobile among Chinese citizens: the influence of environmental concern and perceived social value. Int J Hydrogen Energy 2021;46:18000–10. https://doi.org/10.1016/j.ijhydene.2020.11.099.

[81] Schönauer AL, Glanz S. Hydrogen in future energy systems: social acceptance of the technology and its large-scale infrastructure. Int J Hydrogen Energy 2021. https://doi.org/10.1016/J.IJHYDENE.2021.05.160.

[82] Chapman A, Itaoka K, Hirose K, Davidson FT, Nagasawa K, Lloyd AC, et al. A review of four case studies assessing the potential for hydrogen penetration of the future energy system. Int J Hydrogen Energy 2019;44:6371–82. https://doi.org/10.1016/j.ijhydene.2019.01.168.

[83] Pandev M, Lucchese P, Mansilla C, Le Duigou A, Abrashev B, Vladikova D. Hydrogen Economy: the future for a sustainable and green society. Bulg Chem Commun 2017;49:84–92.

[84] Chen J, Zhang Q, Xu N, Li W, Yao Y, Li P, et al. Roadmap to hydrogen society of Tokyo: Locating priority of hydrogen facilities based on multiple big data fusion. Appl Energy 2022;313:118688. https://doi.org/10.1016/j.apenergy.2022.118688.

[85] De-León Almaraz S, Azzaro-Pantel C, Montastruc L, Pibouleau L, Senties OB. Assessment of mono and multi-objective optimization to design a hydrogen supply chain. Int J Hydrogen Energy 2013;38:14121–45. https://doi.org/10.1016/j.ijhydene.2013.07.059.

[86] Erbach with Sara Svensson G. EU rules for renewable hydrogen. Delegated regulations on a methodology for renewable fuels of non-biological origin. 2023.

[87] Alptekin FM, Celiktas MS. Review on catalytic biomass gasification for hydrogen production as a sustainable energy form and social, technological, economic, environmental, and political analysis of catalysts. ACS Omega 2022;7:24918–41. https://doi.org/10.1021/ACSOMEGA.2C01538.

[88] de Lima LC, Veziroglu TN. Long-term environmental and socio-economic impact of a hydrogen energy program in Brazil. Int J Hydrogen Energy 2001;26:39–45. https://doi.org/10.1016/S0360-3199(00)00050-1.

[89] Hienuki S, Noguchi K, Shibutani T, Fuse M, Noguchi H, Miyake A. Risk identification for the introduction of advanced science and technology: a case study of a hydrogen energy system for smooth social implementation. Int J Hydrogen Energy 2020;45:15027–40. https://doi.org/10.1016/j.ijhydene.2020.03.234.

[90] Aditiya HB, Aziz M. Prospect of hydrogen energy in Asia-Pacific: a perspective review on techno-socio-economy nexus. Int J Hydrogen Energy 2021;46:35027–56. https://doi.org/10.1016/j.ijhydene.2021.08.070.

[91] Fusco M Di, Mendes D, Steuten L, Bloom DE, Drummond M, Hauck K, et al. The societal value of vaccines: expert-based conceptual framework and methods using COVID-19 vaccines as A case study. medRxiv 2022. https://doi.org/10.1101/2022.12.02.22283046. 2022.12.02.22283046.

[92] Akhtar MS, Khan H, Liu JJ, Na J. Green hydrogen and sustainable development – a social LCA perspective highlighting social hotspots and geopolitical implications of the future hydrogen economy. J Clean Prod 2023;395:136438. https://doi.org/10.1016/J.JCLEPRO.2023.136438.

[93] Hultman M, Yaras A. The socio-technological history of hydrogen and fuel cells in Sweden 1978–2005; mapping the innovation trajectory. Int J Hydrogen Energy 2012;37:12043–53. https://doi.org/10.1016/j.ijhydene.2012.06.023.

[94] Yoshida T, Kojima K. Toyota MIRAI fuel cell vehicle and progress toward a future hydrogen society. Interface Mag 2015;24:45–9. https://doi.org/10.1149/2.F03152if.

[95] Hsu C-W, Lin C-Y. Using social network analysis to examine the technological evolution of fermentative hydrogen production from biomass. Int J Hydrogen Energy 2016;41:21573–82. https://doi.org/10.1016/j.ijhydene.2016.07.157.

[96] Garzón Baquero JE, Bellon Monsalve D. From fossil fuel energy to hydrogen energy: transformation of fossil fuel energy economies into hydrogen economies through social entrepreneurship. Int J Hydrogen Energy 2023:48–70. https://doi.org/10.1016/j.ijhydene.2023.06.123.

[97] Simoncini N, Cabaret K, Picard F, Becherif M, Ramadan H, Bethoux O. Social aspects of H2 supply chains: hydrogen technologies genesis and development: the case of myrte platform. Hydrog Supply Chain Des Deploy Oper 2018:293–307. https://doi.org/10.1016/B978-0-12-811197-0.00008-7.

[98] Jepma C. Innovative large-scale energy storage technologies and Power-to-Gas concepts after optimisation. D.8.8. The societal business case for power-to-gas: valuing positive and negative externalities. 2019. 20200713-STOREandGO_D8.8_RUG_The_societal_business_case_for_PtG_valuing_positive_and_negative_externalities.pdf (erig.eu).

[99] FCH J.U.2 Opportunities for hydrogen economy technologies considering the national energy & climate plans (general) 2020;144. accessed Jan 8, 2021.

[100] Hienuki S. Environmental and socio-economic analysis of naphtha reforming hydrogen energy using input-output tables: a case study from Japan. Sustainability 2017;9:1376. https://doi.org/10.3390/su9081376.

[101] Oliveira AM, Beswick RR, Yan Y. A green hydrogen economy for a renewable energy society. Curr Opin Chem Eng 2021;33:100701. https://doi.org/10.1016/j.coche.2021.100701.

[102] Schönauer A-L, Glanz S. Hydrogen in future energy systems: social acceptance of the technology and its large-scale infrastructure. Int J Hydrogen Energy 2022;47:12251–63. https://doi.org/10.1016/j.ijhydene.2021.05.160.

[103] Acar C, Bicer Y, Demir ME, Dincer I. Transition to a new era with light-based hydrogen production for a carbon-free society: an overview. Int J Hydrogen Energy 2019;44:25347–64. https://doi.org/10.1016/j.ijhydene.2019.08.010.

[104] UNEP. Guidelines for social life cycle assessment of products. 2009.

[105] Flynn R, Flynn R, Bellaby P, Ricci M. Risk perception of an emergent technology: the case of hydrogen energy. ESRC Soc. Context. Responses to Risk Netw. Conf. 'Learning about Risk 2005:28–9.

[106] Park J, Ifaei P, Ba-Alawi AH, Safder U, Yoo C. Hydrogen production through the sulfur–iodine cycle using a steam boiler heat source for risk and techno-socio-economic cost (RSTEC) reduction. Int J Hydrogen Energy 2020;45:14578–93. https://doi.org/10.1016/j.ijhydene.2020.03.167.

[107] Schlund D, Schulte S, Sprenger T. The who's who of a hydrogen market ramp-up: a stakeholder analysis for Germany. Renew Sustain Energy Rev 2022;154:111810. https://doi.org/10.1016/j.rser.2021.111810.

[108] Carr-Cornish S, Lamb K, Rodriguez M, Gardner J. Social science for a hydrogen energy future. Australia: 2019.

[109] Upham P, Bögel P, Dütschke E, Burghard U, Oltra C, Sala R, et al. The revolution is conditional? The conditionality of hydrogen fuel cell expectations in five European countries. Energy Res Social Sci 2020;70:101722. https://doi.org/10.1016/j.erss.2020.101722.

[110] Kocsis T, Kuslits B. Multidimensional labelling: closing the sustainability information gap between producers, consumers and sustainability science in the food sector. Periodica Polytech Soc Manag Sci 2019;27:9–16. https://doi.org/10.3311/PPSO.12594.

[111] European Commission. Digital economy and society index. (DESI); 2021.

[112] Holger S, Jan K, Petra Z, Andrea S, Jürgen-Friedrich H. The social footprint of hydrogen production - a social life cycle assessment (S-LCA) of alkaline water electrolysis. Energy Proc 2017;105:3038–44. https://doi.org/10.1016/j.egypro.2017.03.626.

[113] Khan U, Yamamoto T, Sato H. Understanding attitudes of hydrogen fuel-cell vehicle adopters in Japan. Int J Hydrogen Energy 2021;46:30698–717. https://doi.org/10.1016/j.ijhydene.2021.06.195.

[114] Fazli-Khalaf M, Naderi B, Mohammadi M, Pishvaee MS. Design of a sustainable and reliable hydrogen supply chain network under mixed uncertainties: a case study. Int J Hydrogen Energy 2020;45:34503–31. https://doi.org/10.1016/j.ijhydene.2020.05.276.

[115] Andersen O. Providing hydrogen for transport in Norway: a social learning approach. Nord. Transp. netw. North sea comm. Transp. gr., kristiansand, Norway. European Conference on Sustainable goods and Passenger Transport; 2005. https://doi.org/10.13140/RG.2.1.2696.1049.

[116] European Council. Fit for 55. EU's plan for a green transition. Eur Counc 2021. https://www.consilium.europa.eu/en/policies/green-deal/eu-plan-for-a-green-transition/ (accessed Dec 13, 2022).

[117] van de Kerkhof M, Cuppen E, Hisschemöller M. The repertory grid to unfold conflicting positions: the case of a stakeholder dialogue on prospects for hydrogen. Technol Forecast Soc Change 2009;76:422–32. https://doi.org/10.1016/j.techfore.2008.07.004.

[118] United Nations. The sustainable development goals: our framework for COVID-19 recovery. United Nations - Sustain Dev s. f.; 2021. https://www.un.org/sustainabledevelopment/sdgs-framework-for-covid-19-recovery/ (accessed Jan 7, 2022).

[119] Szántó ZO, Aczél P, Csák J, Szabadhegy P, Morgado N, Deli E, et al. Social futuring index. Concept. Budapest: Methodology and Full Report 2020; 2020.

[120] Orbán A, Szántó Z. Intra-European energy solidarity at the core of the European integration process: future possibilities and current constraints. Reinventing Soc. Solidar. Across Eur. 2011:99–120. https://doi.org/10.1332/policypress/9781847427274.003.0007.

[121] Heras J, Martín M. Social issues in the energy transition: effect on the design of the new power system. Appl Energy 2020;278:115654. https://doi.org/10.1016/J.APENERGY.2020.115654.

[122] Kocsis T. Looking through the dataquadrate: characterizing the human–environment relationship through economic, hedonic, ecological and demographic measures. J Clean Prod 2012;35:1–15. https://doi.org/10.1016/J.JCLEPRO.2012.04.020.

[123] Huppert F, Marks N, Michaelson J, Vázquez C, Vittersø J. Personal and social wellbeing. 2018.

[124] European Social Survey. European's wellbeing s. f. 2022. http://www.esswellbeingmatters.org/ (accessed June 14, 2022).

[125] Kocsis T. Finite earth, infinite ambitions: social futuring and sustainability as seen by a social scientist. Soc Econ 2018;40:111–42. https://doi.org/10.1556/204.2018.40.S1.6.

[126] Sovacool BK, Brossmann B. Symbolic convergence and the hydrogen economy. Energy Pol 2010;38:1999–2012. https://doi.org/10.1016/j.enpol.2009.11.081.

[127] Köhler J, Geels FW, Kern F, Markard J, Onsongo E, Wieczorek A, et al. An agenda for sustainability transitions research: state of the art and future directions. Environ Innov Soc Transit 2019;31:1–32. https://doi.org/10.1016/J.EIST.2019.01.004.

[128] Dong ZY, Yang J, Yu L, Daiyan R, Amal R. A green hydrogen credit framework for international green hydrogen trading towards a carbon neutral future. Int J Hydrogen Energy 2022;47:728–34. https://doi.org/10.1016/J.IJHYDENE.2021.10.084.

[129] Székely F, Knirsch M. Responsible leadership and corporate social responsibility:: metrics for sustainable performance. Eur Manag J 2005;23:628–47. https://doi.org/10.1016/J.EMJ.2005.10.009.

[130] Kim J, Lee Y, Moon I. An index-based risk assessment model for hydrogen infrastructure. Int J Hydrogen Energy 2011;36:6387–98. https://doi.org/10.1016/j.ijhydene.2011.02.127.

[131] Hadef H, Negrou B, Ayuso TG, Djebabra M, Ramadan M. Preliminary hazard identification for risk assessment on a complex system for hydrogen production. Int J Hydrogen Energy 2020;45:11855–65. https://doi.org/10.1016/j.ijhydene.2019.10.162.

[132] West M, Al-Douri A, Hartmann K, Buttner W, Groth KM. Critical review and analysis of hydrogen safety data collection tools. Int J Hydrogen Energy 2022;47:17845–58. https://doi.org/10.1016/j.ijhydene.2022.03.244.

[133] Jan van Eck N, Waltman L. VOSviewer Manual 2022. https://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.18.pdf.