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ORIGINAL PAPER

Evolution of the conceptualization of hydrogen through knowledge maps, energy return on investment (EROI) and national policy strategies

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Abstract

In order to address Climate Change and energy dependency challenges, hydrogen (H_2) is emerging as a promising energy carrier. Studies related to its production have conceptualized it as green (GH_2), clean, renewable (RH_2), ecological, and sustainable (SH_2). The aim of this research is to deepen the understanding of the GH_2 concept and to state boundaries between different terms. To reach this objective, a bibliometric analysis of publications indexed in SCOPUS is launched. Also, in order to assess the potential of renewable energy sources (RES) for GH_2 production, a review of the meta-analysis literature on the Energy Return on Energy Invested (EROI) ratio as regards these RES is performed. Additionally, an analysis of main national strategies on GH_2 is launched. Results indicate that the GH_2 concept is gaining remarkable relevance, while the keyword maps show no significant differences between SH_2, RH_2 and GH_2. EROI reveals low average values for the different biomass energy production processes. For their part, GH_2 national strategies focus mainly on solar and wind technologies, albeit leaving the door open to biomass, where EROI could become an adequate metric to guide these strategies towards a low carbon energy path. Although the role of biomass may become fundamental in this energy transition process, given its low EROI values and considering that it is not a totally clean RES, it should be indexed as RH_2, but not always as GH_2. Finally, a proposal that guides a more appropriate use of the term GH_2 is made.

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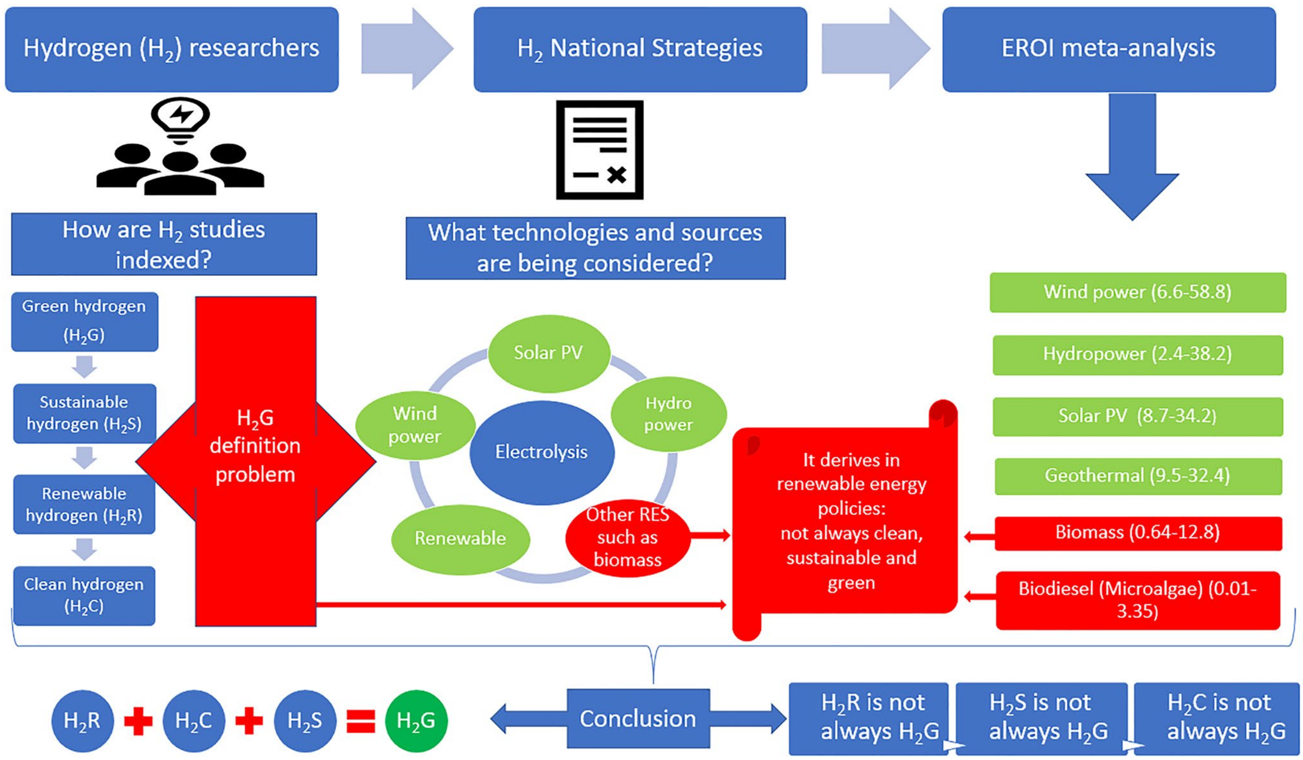
Graphical abstract



Keywords Bibliometric · Energy return on energy invested (EROI) · Green hydrogen (GH_2) · Policy strategy · Renewable hydrogen (RH_2) · Sustainable hydrogen (SH_2)

Abbreviations

CCUS Carbon capture, use and storage
CO Carbon monoxide
CO_2 Carbon dioxide
EROI Energy return on energy invested
EBPT Energy payback time
H_2 Hydrogen
GH_2 Green hydrogen
GHG Greenhouse gases
GW Gigawatt
LCA Life cycle assessment
PM_{10} Particulate matter with diameters of 10 μm
PV Photovoltaic
O_3 Ozone: NEA: Net energy analysis
NO_2 Nitrogen dioxide
RH_2 Renewable hydrogen
RES Renewable energy sources
SH_2 Sustainable hydrogen
SDGs Sustainable development goals
UK United Kingdom
USA United States of America
SDGs Sustainable development goals
SO_2 Sulfur dioxide

Introduction

In recent decades, humankind has viewed two directly related problems with great concern: On one hand, dependence on non-renewable energy sources (non-RES) such as fossil fuels. On the other hand, the environmental damage caused by overuse of fossil fuels (Bamati and Raoofi 2019). Multiple initiatives have been generated from these problems, primarily among which are the use of renewable energy sources (RES) and the development of electric cars (Hannan et al. 2017; Herez et al. 2020), leading to many nations being in the process of transitioning to RES (Diesendorf and Wiedmann 2020; REN21 2021).

To address these challenges, hydrogen (H_2) is emerging as a sustainable energy carrier. Its use as a non-polluting energy vector is gaining relevance and is considered one of the most promising in the future (Ni et al. 2007; Hosseini and Wahid 2016; Osman et al. 2020a). Although there are other substances in nature that contain H_2, water is one of the most abundant substances on the planet. The great dream of propelling an automobile fueled by water might well be materialized in H_2, and herein lies its greatness.

Green hydrogen (GH_2), energy return on energy invested (EROI) and national energy strategies

One of the main problems in obtaining H_2 is that in nature it is not found in a pure state, requiring the application of different separation processes. These techniques include thermolysis, reforming, gasification and electrolysis (Carmo et al. 2013; Hosseini and Wahid 2016; Çelik and Yıldız 2017). Three main classifications associated with the different H_2 production techniques and their environmental impact have been established: (i) Gray H_2, being the most widely used and the least environmentally friendly, as its generation requires fossil fuels using hydrocarbon reforming and pyrolysis, (Nikolaidis and Poullikkas 2017; Newborough and Cooley 2020); (ii) Blue or low-carbon H_2, while still requiring fossil fuels, achieves carbon emission reductions through capture and storage (Noussan et al. 2021); (iii) Green hydrogen (GH_2), which is produced from RES, using electrolysis, with a near-zero carbon production pathway (Kakoulaki et al. 2021). At present, it is estimated that 95% of H_2 production is obtained by processes associated with the exploitation of fossil fuels, 4% using electrolysis and only 1% from biomasses (Hosseini and Wahid 2016).

GH_2 is defined as the set of methods, techniques and processes employed to produce H_2 using RES. As a clean (CO_2-free) renewable fuel, its large-scale production makes it a sustainable alternative for future generations (Nikolaidis and Poullikkas 2017; Noussan et al. 2021; Rabiee et al. 2021; Kim et al. 2021; Mohideen et al. 2021). Velazquez and Dodds (2020) argues that there is no universally accepted definition for GH_2, which may result in technologies that do not meet currently accepted standards (Velazquez and Dodds 2020). Therefore, it is important to determine whether research on GH_2 has established boundaries with respect to other terms such as clean H_2, sustainable hydrogen (SH_2), renewable hydrogen (RH_2), and ecological H_2, or whether they are being understood as synonyms. Hereafter, the term"H_2 concept" will be used to refer to the above-mentioned set of terms to synthesize the wording. Accordingly, a universally accepted concept of GH_2 that defines the types of RES and the technologies it encompasses, can standardize the certification processes, thus, avoiding future disputes in the international commercialization process.

Net energy analysis (NEA) assesses how much "net" energy a given energy carrier can provide to society, once all the energy costs incurred along its supply chain have been subtracted. A key indicator for NEA analysis is the energy return on (energy) investment, identified by the acronym EROI or EROEI (Raugei 2019). EROI is defined as the ratio between the total energy produced or returned by an energy source and the energy invested or consumed to obtain it (Hall et al. 2014; Arvesen and Hertwich 2015; Walmsley et al. 2018; Fabre 2019; Capellán-Pérez et al. 2019; Diesendorf and Wiedmann 2020; Wang et al. 2021; Jackson and Jackson 2021). Together with the energy payback time (EBPT), EROI is the most widely used metric to evaluate the energy benefit of different energy technologies (Bhandari et al. 2015; Jackson and Jackson 2021).

Specifically, through EROI, a relationship can be established between the energy lost or not used by society and the net energy that is available to society (Arvesen and Hertwich 2015). This relationship between the energy available and the energy consumption required to produce it can be interpreted as the efficiency of a technology to provide energy (Hall et al. 2014; Fabre 2019). Therefore, it is estimated that a decrease in EROI below a certain limit could affect the availability of energy for certain activities, compromising the operation of certain systems within society. Correspondingly, a reduction in EROI is reflected in negative economic results, thus favoring investment in those energies that offer higher EROI (Jackson and Jackson 2021). Therefore, NEA in combination with other sustainability indicators, could be considered as an adequate metric when defining energy technologies as sustainable and/or green.

When estimating the EROI of different RES technologies, many methodological discrepancies appear due to the databases used (Carbajales-Dale et al. 2014; Diesendorf and Wiedmann 2020), the characteristics of the variables (e.g., a megajoule (MJ) of electricity versus a MJ of heat energy) and system boundaries. In regard to these boundaries, the following distinction is necessary when estimating the EROI of different technologies: standard EROI (EROIst),[1] EROI 'at point of use' (EROIpou)[2] (Capellán-Pérez et al. 2019) and extended EROI (EROIext)[3] (White and Kramer 2019; Raugei 2019; Capellán-Pérez et al. 2019; de Castro and Capellán-Pérez 2020; Diesendorf and Wiedmann 2020), the latter being traditionally more used to assess fossil fuels. A critical review of the main modeling tools currently used to assess energy transition can be found in (de Blas et al. 2019; Samsó et al. 2020). As explained by these authors, there are a wide range of modeling forecasting

[1] The calculation includes the on-site energy production or extraction costs and the cost of the items used (energy cost) (Capellán-Pérez et al. 2019).

[2] This EROI calculation encompasses production to transportation to the point of consumption, including production, processing and transportation (Capellán-Pérez et al. 2019).

[3] This case also includes the energy consumption necessary to supply and use certain amounts of energy by the end user (Capellán-Pérez et al. 2019).

tools to design alternatives for a more sustainable future. Among the most relevant in relation to our area of study are: "energy models", which focus on energy systems, and "Integrated Assessment Models" (IAMs), with a more extensive approach to the eco-social-environmental systems and their interrelationships [31]. IAMs are complex software that includes mathematical models used to portray fundamental dimensions for the de-carbonization of the economy (i.e., environmental, social, economic, climatic, and also institutional dimensions). Decision-makers increasingly rely on these IAMs to guide their decisions regarding energy transition(Samsó et al. 2020). These models are fundamental tools in order to model transportation, mineral use and static and dynamic[4] EROI estimations (MEDEAS 2017; de Blas et al. 2019; Samsó et al. 2020).

Given the great expectations created around the production and commercialization of GH_2, several countries have identified the huge potential offered by this fuel in environmental and economic terms. This has led them to propose relevant specific policies, some examples being the European bloc (EU-27 and the United Kingdom (UK) (Kakoulaki et al. 2021), USA (Clark and Rifkin 2006), China (Huang and Liu 2020), Japan (Chaube et al. 2020), and Chile (Armijo and Philibert 2020; Chile 2020). Interpretation of these strategies may help to determine how those countries that show the most progress are actually conceptualizing GH_2.

Scientometry applied to GH_2

The necessary natural conditions are not nearly enough when it comes to install GH_2 production capacities, the scientific capabilities to efficiently assimilate the processes of technology transfer and development are also important. Identifying where knowledge is generated and which clusters take special relevance is crucial, as this allows policies that provide effective actions for managing technology transfer to be formulated. Likewise, the identification of hot topics being studied by the scientific community helps to focus on those technologies with greater potential, as well as identifying relevant topics that are currently receiving little attention. In this sense, researchers play a fundamental role in the symbiotic nature between science and industry in terms of providing information of high scientific rigor that efficiently advances the implementation of those technologies that may have a substantial impact on the future of humanity, providing clear indicators for stakeholders within the sector.

Bibliometric studies can be used to visualize an area of knowledge, reflecting the main indicators to provide a quick and intuitive understanding of the social and cognitive structure of the subject under analysis (Garechana et al. 2012). Examples of the most recent and impactful bibliometric studies related to environmental concepts have focused on bringing conceptual clarity to the terms "circular economy" and "sustainability" (Geissdoerfer et al. 2017), and a complete comparative analysis of the three concepts of "circular economy"; "green economy" and "bioeconomy" (D'Amato et al. 2017). Both studies address the concepts in specific terms, without including interpretations derived from the definitions, i.e., only general keywords were included without including interpretations derived from other terms. On the other hand, the study by Garrido et al. (2019) explores the association between supply chain performance and RES incorporation using the keywords associated with the existing RES typologies: biofuel, biomass, bioethanol, ethanol, geothermal energy, wind energy, wind power, solar energy, thermal energy, photovoltaic cells, ocean energy, hydroelectric energy, hydropower and landfill gas. The difference with respect to the previous approach is that in this case, the search includes terms derived from the global concept of RES.

As regards the concept of GH_2, being a relatively new term (US Department of Energy 1995; Clark and Rifkin 2006), bibliometric studies on this concept have not been specifically addressed. However, topics related to H_2 have already been addressed, such as the study by Ming-Yueh (2008) that explored the characteristics of the literature on H_2 energy from 1965 to 2005. It found that growth of scientific production in the said period grew at a rate of about 18%, revealing leadership by the USA, Japan and China (Ming-Yueh 2008). Hydrolysis or hydrolytic dehydrogenation of sodium borohydride was recently addressed (Abdelhamid 2021), H_2 production from organic raw materials, industrial wastes or byproducts (Jiménez-Castro et al. 2020), as well as capture, storage and production methods (Chanchetti et al. 2019; Liu et al. 2020; Osman et al. 2020b). In 2011 a study presented technological S-curves integrating bibliometrics and patenting for fuel cell and H_2 energy technologies, determining that technologies used to generate and store H_2 had not yet reached technological maturity (Chen et al. 2011). Later, in 2020, Alvarez-Meaza et al. (2020) researched bibliometrics and patents to generate technology knowledge maps of fuel cell electric vehicles to be able to forecast future trajectories of research trends and expected scenarios. Other authors have studied H_2 production methods with a clean, sustainable approach produced biologically, usually by algae and bacteria, and microbial electrolysis cells (MEC), such as biohydrogen (Leu et al. 2012; Hsu and Lin 2016; Osman et al. 2020a; Zhao et al. 2020). However, the results shown in these studies establish no relationship with the term GH_2. The strategies associated with the production of GH_2 have been linked to more

[4] The dynamic EROI covers all energy costs of the entire system, including feedback, and can be calculated dynamically, i.e., taking into account time periods (Capellán-Pérez et al. 2019).

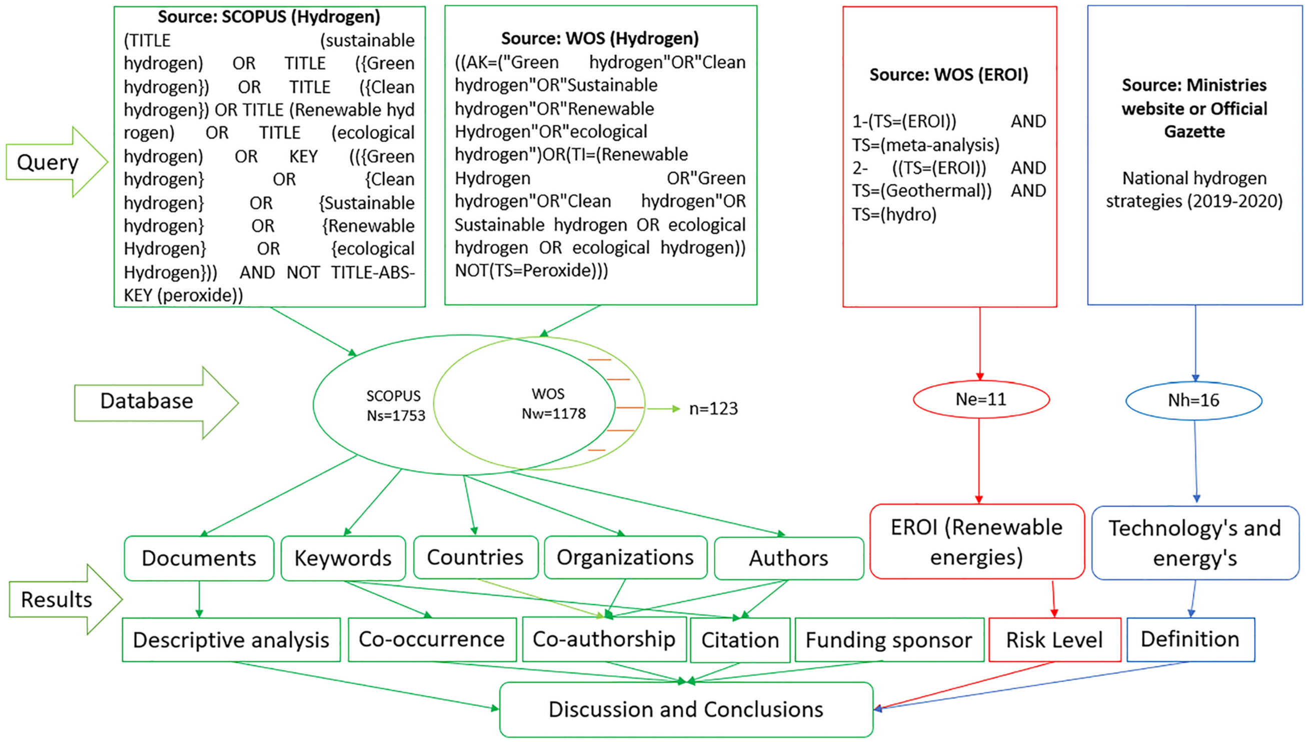


Fig. 1 Structure of the present investigation's methodology

traditional RES production processes such as solar, wind and hydro, (Kazi et al. 2021; Chien et al. 2021). Biomass is also recognized, albeit with lower potential (Kakoulaki et al. 2021).

The objective of this research is to better understand the concept of green GH_2, through a bibliometric analysis of publications indexed in the SCOPUS database, in order to comprehend the boundaries between the term GH_2 and others used synonymously. Additionally, a review of the existing meta-analysis literature on EROI applied to different RES is performed with the aim of evaluating its potential for GH_2 production. Finally, an analysis of the main national strategies on GH_2 is launched. The rest of the article is organized as follows: Sect. 2 explains the methodology utilized to meet the research objective. Sections 3 and 4 present the results obtained and the discussion respectively, and finally, the conclusions are illustrated in Sect. 5.

Material and methods

Figure 1 illustrates the methodology developed for the present study. A total of three stages have been performed. The first stage focuses on a bibliometric analysis of the scientific production of publications on the concept of H_2 (in green); the second, on the literature review of meta-analysis studies on EROI (in red); and the third stage, on the review of main national strategies on GH_2 (in blue).

Bibliometric analysis

As explained, the most recent and impactful bibliometric studies related to environmental concepts have followed two different approaches. This study follows the approach of (Geissdoerfer et al. 2017; D'Amato et al. 2017) (i.e., only including the search terms encompassed in the "H_2 concept").

Two principles were defined for the choice of database: the first was based on the impact of the source and the second on the greatest coverage in terms of the number of indexed documents. This made it possible to focus the analysis on the SCOPUS and Web of Science (WOS) databases. Figure 1 illustrates the methodology used for the bibliometric analysis, (shown in green). On April 16, 2021, the defined terms, representing the main meanings that can be related to the evolution of the concept of H_2, were introduced as a query in the title and as an author keyword; to avoid indirect references to the term, the abstract was not searched. This yielded a total of 1753 documents in SCOPUS and 1178 in WOS, with a coincidence between the two sets of 1055 and a difference of 123 in the number of WOS documents not included in SCOPUS.

To analyze the overlap between the databases, four steps were defined. In the first step, the smaller dataset (WOS) was added to the larger one (SCOPUS). In step two, a unique Digital Object Identifier (DOI) was assigned to those documents that did not have one. In step three, duplicates were removed from the DOI column. And in step four, a second simplification was applied taking the title column into account. A decision was taken to use the SCOPUS database because it includes 89.56% of the WOS documents and has a higher indexing coverage. We also added the 123 non-content WOS documents. These data were analyzed using VOSviewer software, which allows bibliometric networks of countries, organizations and authors to be constructed and visualized in order to identify and characterize the clusters and their interaction with the subject matter (Van Eck and Waltman 2010, 2020), based on co-authorship, co-occurrence and citation analysis (Sharifi 2021).

The initial step within the first stage was a descriptive analysis based on the growth of the documents associated with each search concept (see Sect. 3.1.1.). Then, in Sect. 3.1.2, a keyword map was developed and used to determine the relationships of the terms used with the different production methods, and to analyze the main research trends in these topics, as well as the maturity of each concept (Guan et al. 2021; Wu et al. 2021). The analysis by country was carried out by developing a co-authorship map to assess scientific productivity and collaborative networks (Sect. 3.1.3.). The funding by country analysis identifies which countries have provided greater financial support and how this is reflected in the scientific productivity for the topic studied (Sect. 3.1.4.). In the case of organizations producing knowledge, a co-authorship map was developed to determine the levels of collaboration and whether these are in a national or international context (Sect. 3.1.5.). Finally, the co-authorship map was used to determine which researchers are the most productive and collaborative, enabling us to identify the topics that are allowing them to achieve this relevance (Sect. 3.1.6.).

EROI for renewable energy sources

The second stage of the analysis is aimed at establishing the limits of the GH_2 concept, based on the efficiency expressed in the EROI standard (see Fig. 1 in red).

Despite several studies having focused on performing meta-analyses to identify the EROI values of RES (Bhandari et al. 2015; Walmsley et al. 2018; Capellán-Pérez et al. 2019), as far as we know, there is no paper that performed EROI estimates for GH_2.

Therefore, in order to establish these limits, the following steps have been followed:

i. A review of main literature on current meta-analysis studies published in WOS centered around the EROI calculations for the different RES with the potential to produce H_2. A meta-analysis consists of collecting and statistically analyzing data through methodical reviews. This tool has been widely used and disseminated in health sciences and clinical research, progressively extending to other areas such as life cycle assessment (LCA) and EROI. (Bhandari et al. 2015; Walmsley et al. 2018). As shown in Fig. 1 (in red), the search was performed under the queries (meta-analysis and EROI); in the case of geothermal energy searched by (EROI and geothermal) and for hydropower (EROI and hydro) because when combined with "meta-analysis" no results appear.

ii. In order to categorize the EROI values, in addition to Prananta and Kubiszewski (2021), the scale proposed by Capellán-Pérez et al. (de Blas et al. 2019) has been used. The IAM used by these authors is an energy-economy-environment model (i.e. the MEDEAS model) that computes the EROI of each technology and also the whole energy system endogenously and dynamically. This makes it possible to identify potentially hazardous situations of growth in gross energy production that does not lead to an increase in the net energy consumed by society, which has been called the "energy trap" (de Blas et al. 2019; Capellán-Pérez et al. 2019). According to the scale proposed by these authors:

"EROI:> 15:1, no risk; <10-15:1, low risk; <5-10:1, dangerous; <5:1, very dangerous; <2-3:1, unfeasible system.".

The proposed scale promotes a different view compared to a large part of the literature on NEA that centers on exceeding the "break-even point" (EROI of 1:1). Promoting values higher than 1:1 for EROI mean that not only can the elementary needs of humanity such as food, shelter and clothing be met, but also aspects such as the arts, healthcare, education, and the well-being of the average citizen are supported, as high-quality energy contributes to social well-being (Hall et al. 2014; Fizaine and Court 2016; Prananta and Kubiszewski 2021).

In general, we consider RES classified as low or no risk viable to produce GH_2.

National GH_2 strategies

The third stage of the analysis includes a review of national H_2 strategies, identified using the most relevant global sources of information related to these issues (i.e. the reports of the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) (see Fig. 1 in blue)). These reports present a compilation of the countries

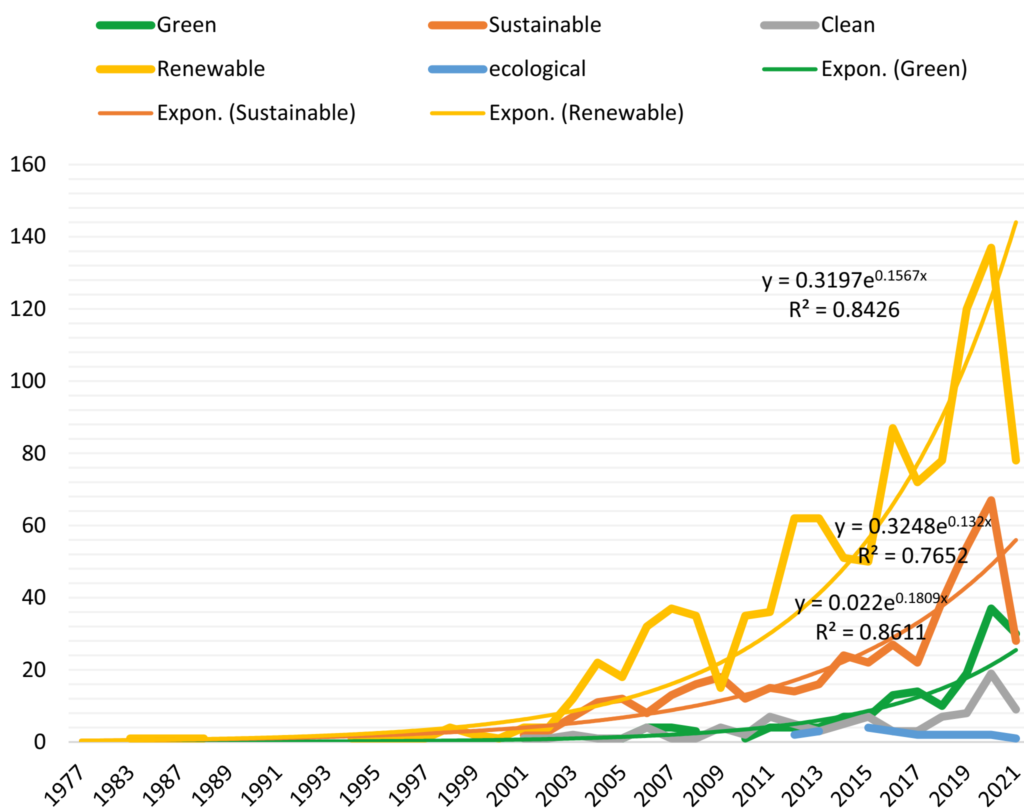


Fig. 2 Evolution of publications related to the "H_2 concept", indexed in WOS and SCOPUS, (1977-April 2021). *Source*: Own elaboration based on SCOPUS and Web of Science (WOS), 2022

that have published these strategy documents. Since 2019, Japan and Korea have published their national H_2 strategies, joined in 2020 by France, Australia, Canada, Chile, Germany, Netherlands, Russia, Norway, Portugal, Spain, together with the European Commission. During 2021 Hungary, Czech Republic and UK did likewise (IRENA 2020a; International Energy Agency 2021). In the review, we have identified which RES and technologies are being declared by the countries in their national roadmaps for H_2 production. These strategies have subsequently been analyzed using the websites of the ministry in charge of energy development in each country (in the case of Portugal, the nation's official gazette in the form of a resolution and in the case of the EU, the page for the European Commission has been consulted).

In general, three types of strategies have been identified. The first one promotes hydrogen production using the traditional resources available to the countries, including fossil fuels using carbon capture, use and storage (CCUS) methods and RES. The second is promoted by a group of countries with little potential to produce hydrogen, therefore, they focus on promoting the consumption and creation of technologies for the production and consumption of this energy carrier. The third group promotes the production of GH_2 only from the use of RES. Our analysis focuses on this last group of countries.

Results

Results of the bibliometric study

Descriptive analysis of the evolution of the H_2 concept

Publications related to the H_2 concepts addressed have been recorded since 1977, with discrete values until 2000, after which growth has been exponential up to the present (Fig. 2). Of a total of 1,751 records, 60.4% are associated with RH_2, this term being the first to be used in 1977. A year later, the concept of ecological H_2 appeared, which has been used very little (1.6%). In 1989, sustainable H_2 was the second most used concept with 24.8%. In 1998, with only 5.4%, clean H_2 appeared, which has shown a very discreet evolution. The term GH_2 proves to be a more modern concept that has been used in scientific research mainly in the twenty-first century (2006) and represents 9.2%, and although it shows exponential growth, its growth rate is lower than that of the terms renewable and sustainable. In 1995 a document made

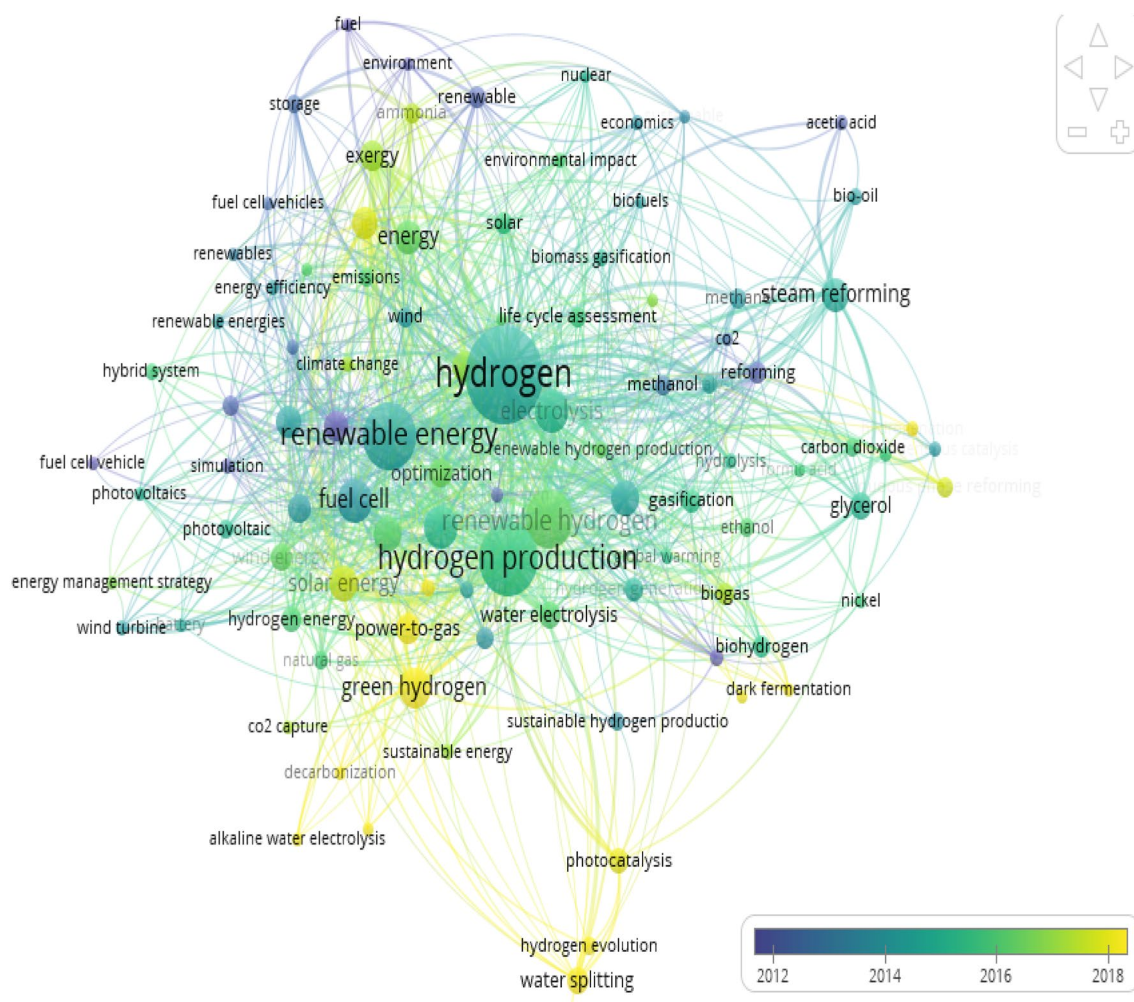


Fig. 3 Map of co-occurrence of author keywords in "H_2 concept" related studies, (1977-April 2021). *Source*: Own elaboration based on SCOPUS, 2022

direct mention of the term "green hydrogen" in its title (US Department of Energy 1995) and despite not being indexed as a scientific publication, it constitutes a reference in the use of the term.

Keyword analysis, relationships and trends

The co-occurrence map of author-defined keywords was used to identify the most frequently addressed or hot topics and their maturity or notability over time (Fig. 3). Among 3,243 keywords, only 169 have a frequency equal to or greater than 5 occurrences. Consequently, the most general terms such as "hydrogen", "hydrogen production" and "renewable energy" are notable for their frequency and number of links. The words most frequently used to characterize H_2 within the terms defined in this study are "renewable hydrogen" together with "renewable hydrogen production", which together account for 135 occurrences and link to 370 other words on 521 occasions. In second place, "green hydrogen" together with "green hydrogen production" amount to 66 occurrences and link to 216 words on 270 occasions. Generally speaking, all terms are relatively recent (since 2012). In the case of "renewable hydrogen" its average converges at 2016, whereas "green hydrogen" is a more current trend averaging around 2018. The other words "sustainable hydrogen" (17), and "clean hydrogen" (10) have been used very little.

The map characterizing the RH_2 concept (Fig. 4) shows a group of RES that have been addressed within this theme. The most notable appearances are: "Solar energy*", "biomass", "biogas*" and "wind*". It is important to stress that the term "hydropower*" has little incidence despite being the most produced RES in the world (IRENA 2020b). The most prominent technologies are electrolyzers and fuel cells.

Unlike in the RH_2 map (Fig. 4), in the GH_2 map (Fig. 5) there is little use of the terms linked to certain RES such as

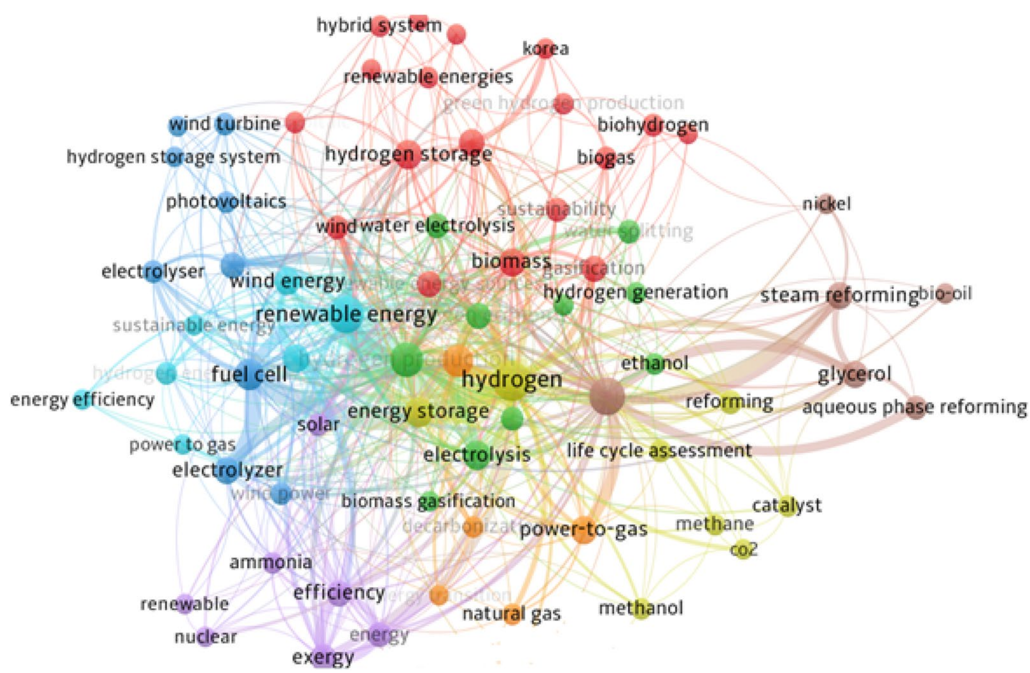


Fig. 4 Co-occurrence map of author keywords in RH_2 related studies. *Source*: Own elaboration based on SCOPUS, 2022

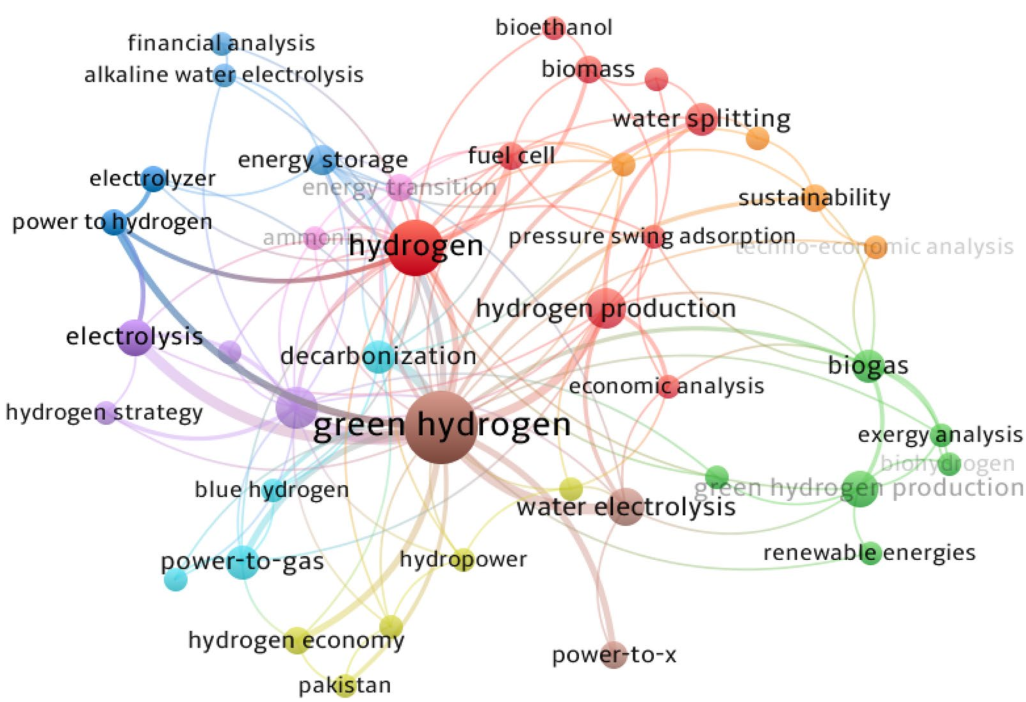


Fig. 5 Co-occurrence map of author keywords in GH_2 related studies. *Source*: Own elaboration based on SCOPUS, 2022

solar and wind. Instead, the terms “biomass” and “biofuels” are much more prominent. In terms of technology, the electrolysis process and gas-fired power are prominent.

As regards the term SH_2 (see Fig. 6), new relevant terms appear (e.g. "steam reforming", "glycerol", "bio-hydrogen"…). In fact, SH_2 is associated with a broader range of

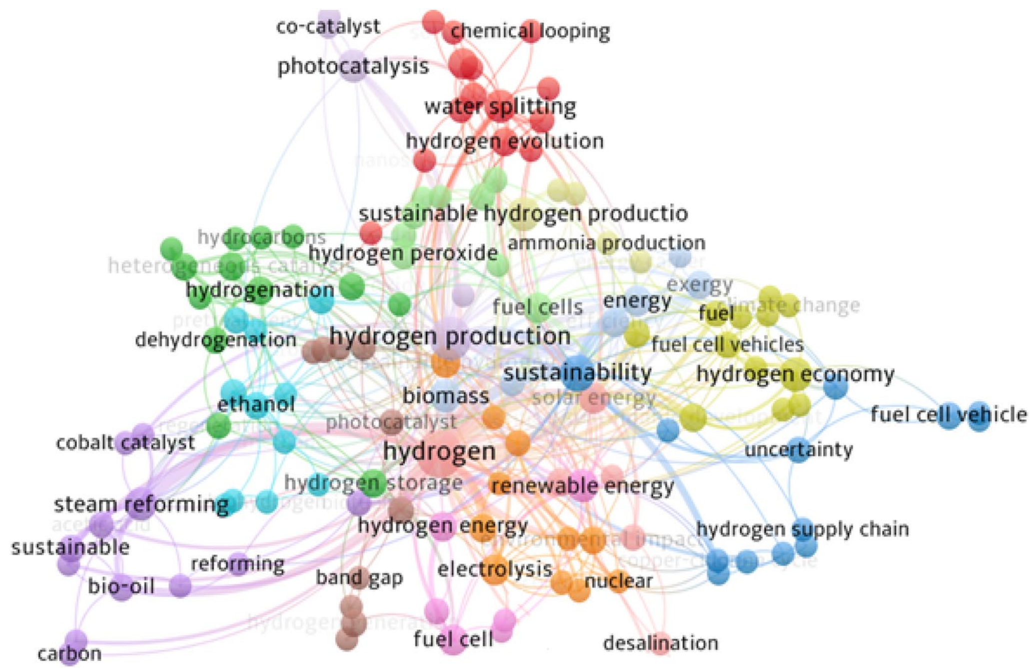


Fig. 6 Co-occurrence map of author keywords in SH_2 related studies. *Source* Own elaboration based on SCOPUS, 2022

terms related to the full H_2 production supply chain (e.g. battery cell vehicles, H_2 storage…). Terms linked with non-RES (e.g. nuclear and natural gas) are also noticeable. These non-RES appear when H_2 sustainability is sought by incorporating RES but maintaining the participation of traditional fuels (i.e., combining RES and non-RES). See, for example, the study of Kodama et. al. (2006), focusing on the solar receiver-reactor systems to convert high concentrated solar fluxes into chemical fuels by endothermic reforming of natural gas at high temperatures (Kodama et al. 2006); and that of Möller et al. (2006), on solar steam reforming of natural gas.

For its part, "steam reforming" is one of the fundamental technologies for obtaining H_2, either from fossil fuels or RES, such as biomass (Nabgan et al. 2017). This technology requires high temperatures, which, if conventional methods are used, can lead to an increase in GHG emissions (Zheng et al. 2021). A number of studies have focused on incorporating waste heat for H_2 production to improve efficiency and reduce GHG (Zheng et al. 2020b, a; , 2021; Moogi et al. 2021). The results of this line of research may be a fundamental key to the sustainability of H_2 production. Despite the slight differences observed, the large overlap of words contained in the RH_2, SH_2, GH_2 maps indicates that these terms are often considered synonymous and are therefore used interchangeably. However, it is important to note that the keywords "steam reformed" and "nuclear" appear on the RH_2 map (Fig. 5) and SH_2 map (Fig. 6) but not on the GH_2 map (Fig. 4). These being the most notable differences between the GH_2 map and the other two (i.e., Fig. 5 vs. Figs. 4 and 6).

Country analysis

The record of scientific publications covered in the GH_2 concept is dominated by the USA, with 273 papers, collaborating with 36 countries on 100 occasions; China with 201 papers, collaborating with 34 countries on 130 occasions and Germany, with 133 collaborating with 27 countries on 78 occasions. Rounding out the top ten were the UK, Canada, Spain, Italy, Japan, India, and Turkey. On the other hand, the low productivity of countries in less developed regions, especially in Latin America and Africa, is evident (Fig. 7). Another important characteristic shown in Fig. 7 is productivity over time, which places the USA as a pioneer in the subject, and its average publication rate converges in 2011, while for China this occurs in 2017, establishing it as an emerging nation in the subject.

Analysis of financing by country

A fundamental aspect for developing research is the availability of funding. Accordingly, countries that allocate more financial resources are expected to improve their scientific productivity. As shown in Fig. 8, the agencies that have financed more than 10 documents are led by Chinese, North American and European organizations, which is closely related to the leadership that these countries have in this

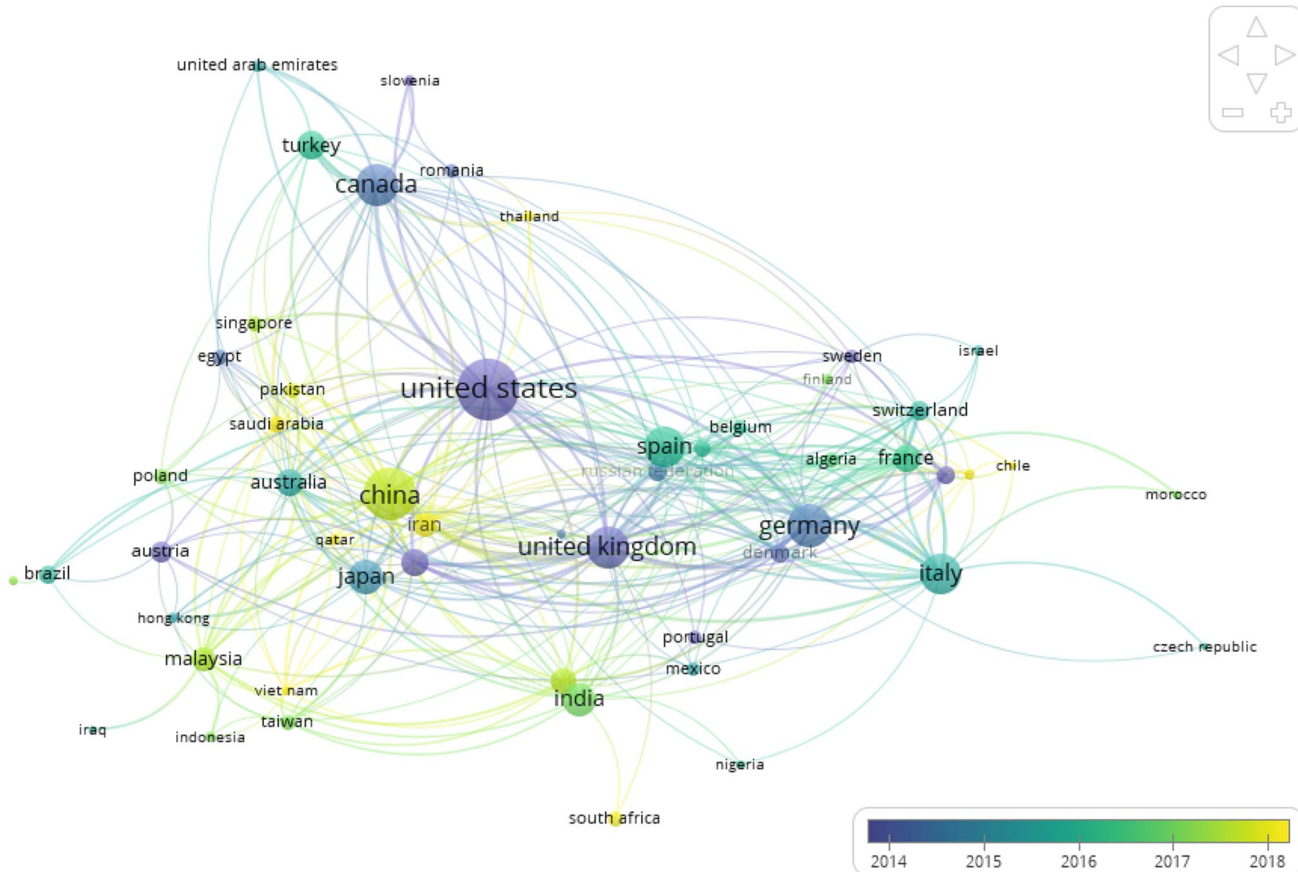


Fig. 7 Co-authorship map of countries on "H_2 concept" related research, (1977-April 2021). *Source*: Own elaboration based on SCOPUS, 2022

area. Overall, 64% of the publications have received funding, suggesting that the institutions are very interested in this subject.

Analysis by organization

In general, there is little collaboration between organizations. Collaboration is mainly national in scope, e.g., Ontario Tech University (Canada), which leads in this aspect, collaborating mainly with the University of Waterloo (Canada), University of Western Ontario (Canada), American University of Sharjah (United Arab Emirates), Gaziantep University (Turkey) and Argonne National Laboratory (USA). In second place is the cluster formed by the Chinese Academy of Sciences and its subordinate, the University of Chinese Academy of Sciences, which collaborates mainly with other Chinese universities. The National Renewable Energy Laboratory, which leads a cluster in the USA, also stands out. A significant number of organizations that appear on the right edge (Fig. 9), despite showing results on the subject, do not do so in a collaborative manner.

Analysis by authors

Productivity at the author level is led by the Canadian researcher Dr. Ibrahim Dincer from Ontario Tech University, Oshawa, Canada, with 57 papers in collaboration with 14 researchers, mainly from Canada and Turkey (Fig. 10). His research areas cover the topics of heat and mass transfer, fuel cell systems and H_2, among others. Other clusters with a productivity of 10 and 15 papers and grouping between 10 and 15 researchers, mainly Canadian and Chinese, can be observed in the center.

In the context of Fig. 10, Dr. John A. Turner, who belongs to the National Renewable Energy Laboratory, United States, researching direct conversion systems (photoelectrolysis) for H_2 production from sunlight and water, catalysts for H_2 and oxygen reactions, seems of little relevance to this co-authorship network. However, this researcher is notable in this analysis for being the most cited, with only six papers he has achieved 3,308 citations, 3,303 of which belong to the publication "Sustainable hydrogen production"(Turner 2004). This work helps to understand the concept of sustainability, mentioning solar, wind, nuclear and geothermal energy as the main RES for SH_2 production. Methods have

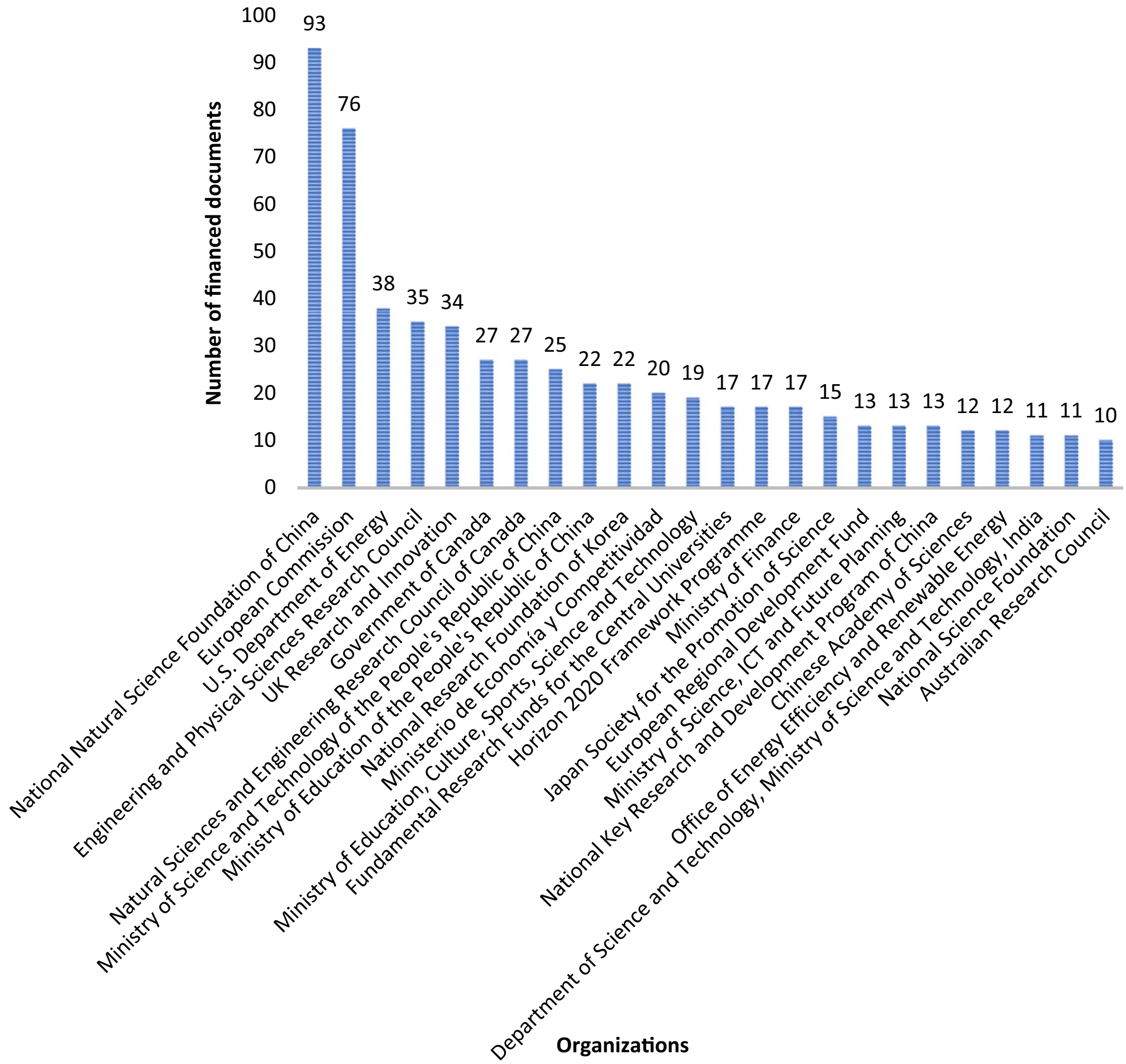


Fig. 8 Major funding organizations for "H_2 concept" related research. *Source*: Own elaboration based on SCOPUS, 2022

mentioned thermal chemical cycles using heat, water electrolysis and biomass processing using technologies such as reforming and fermentation (Turner 2004). Both the methods and resources cited can be linked to GH_2 production but are not limited to this concept, as they include energies not defined as renewable.

Results around EROI values of candidate energies for GH_2 production

Table 1 shows the EROI values according to meta-analysis studies for RES, including the scope of analysis, categorization, and source used. Main results as regards the revision of theses meta-analysis illustrate that:

I. The EROI estimated for wind power by Walmsley et al. (Walmsley et al. 2017) at 19 sites in New Zealand, show that these metrics are greatly affected by average wind speed and blade diameter, resulting in variation from project to project, with the average being 34.7, despite showing a high value the authors consider it unreliable due to the intermittency of high generation. Therefore, they propose pairing wind generation with flexible base load generation, such as hydroelectric, for the complementary integration of wind farms into the national power grid, helping to overcome the drawback of wind intermittency. However, in the case of GH_2 production, intermittency would not have the same negative impact as when used for interconnected electricity generation. Another meta-analysis study suggests that hydropower and wind power show great potential if geographic locations that provide adequate generation potential are chosen, with their performance match-

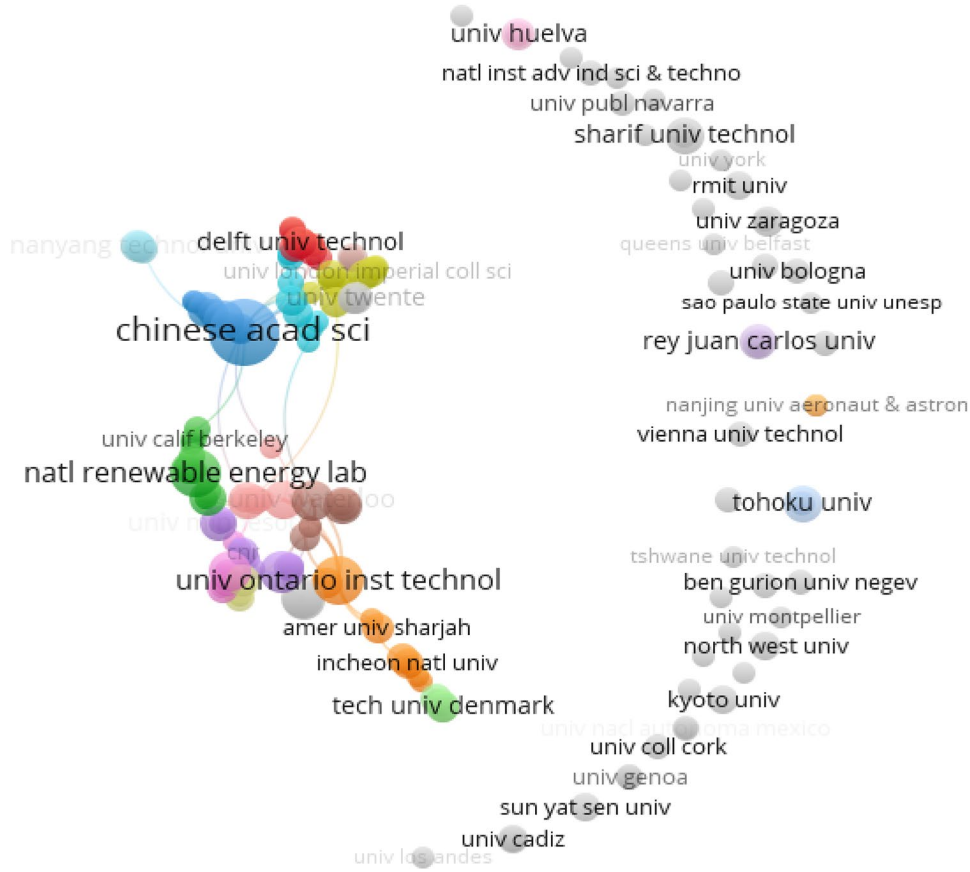


Fig. 9 Co-authorship map of organizations on "H_2 concept" related research, (1977-April 2021). *Source*: Own elaboration based on SCOPUS, 2022

ing even that of coal-fired power plants (Walmsley et al. 2018).

II. The mean EROI values shown by Bhandari et al. (2015) ranged from 8.7 to 34.2, for crystalline Si and thin film PV technologies, published in the period 2000–2013, based on a review of 232 sources, of which 11 provided information, normalized for the variables (system lifetime, solar insolation, and module efficiency) that are driving the life-cycle performance of the PV system. The author indicates that, due to the incorporation of new processes and reductions in the amount of material needed to manufacture solar cells, it is likely that photovoltaic technology will reach a maximum EROI with respect to carbon in the future.

III. Results obtained by Prananta and Kubiszewski. (2021) state that when comparing biofuel with other RES, it provides the lowest EROI value, with a mean value of 3.92. Although the ratio is higher than 1:1, it was classified as not feasible for development. Therefore, they propose certain improvements that they believe are necessary for Indonesia's biofuel program to move forward.

IV. In general the lowest EROI values can be seen in the study by Ketzer et al. (2018) This provides results on the energy products of algae based on a meta-analysis of LCA and EROI. The range of the EROI in this case varies from 0.01 to 3.35 according to the research consulted, which indicates considerable uncertainty for this RES as it is classified as unfeasible. This study highlights the sustainability of algae as an energy carrier in the context of green energy.

V. Wang et al. (2021) found that bioenergy EROI values varied among biomass conversion technologies, attributing the best results to the physical conversion process. This study promotes the use of biomass in the Chinese national context. The authors argue that feedstock availability, national strategic needs and economic efficiency are important factors in the selection of a biomass conversion route. Regarding the different types of biofuels, they indicate that those from wood and straw residues showed better EROI values than those based on cereals. On the other hand, they emphasize China's problems with biomass residues, especially crop residues, when improperly treated, as in the case of open burning, which causes a significant negative impact on the environment. The development of grain-based biofuels is also recognized as a threat to food security.

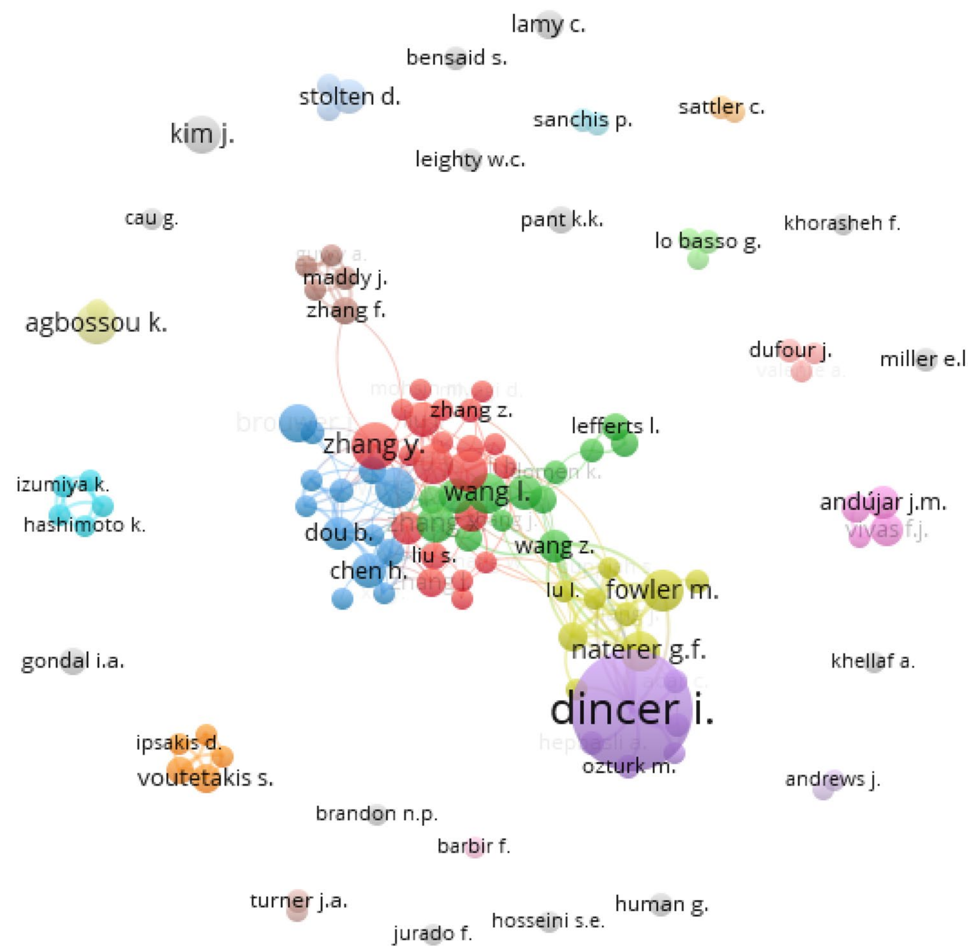


Fig. 10 Map of co-authorship of researchers on "H_2 concept" related research, (1977- April 2021). *Source*: Own elaboration based on SCOPUS, 2022

Table 1 EROI values according to meta-analysis study for RES. *Source* Own elaboration, 2022

Type	SCOPE	EROI			Category	Source
		Min*	Median	Max		
Wind power	New Zealand	6.6	34.7	58.8	No Risk	(Walmsley et al. 2017)
Hydropower	World	2.4	20.3	38.2	No Risk	(Walmsley et al. 2018)
Solar PV	World	8.7	21.5	34.2	No Risk	(Bhandari et al. 2015)
Biomass (Physical process)	China	–	12.8 *	–	Low Risk	(Wang et al. 2021)
Biomass (Biological process)	China	–	4.4*	–	Very Risk	(Wang et al. 2021)
Biomass (Physical Chemical)	China	1.26	4.3*	7.41	Very Risky	(Wang et al. 2021)
Biomass (Biofuel)	World	0.64	3.9*	6.7	Very Risky	(Pránanta and Kubiszewski 2021)
Biodiesel (Microalgae)	World	0.01	1,6	3.35	Not feasible	(Ketzer et al. 2018)
Geothermal	Iceland	9.5	20.9	32.4	No Risk	(Atlason and Unnthorsson 2013)

*Mean calculated by the authors

VI. As regards geothermal energy, meta-analysis studies on EROI are sparse, resorting to the values determined for the case of the Nesjavellir geothermal power plant, the second largest geothermal power plant in Iceland, in the study by Atlason and Unnthorsson (2013), showing that this type of project is feasible when natural conditions favor it, in this case with an EROI value of 32. 4, however, excluding hot water, this was reduced to 9.5.

Table 2 Technologies described in global GH_2 strategies. *Source*: Own elaboration, 2022

Country	Electrolyzer capacity (GW)	Technologies	Energy	Project date	Source	Year
France	6.5	Electrolysis	Renewable	2030	(Pompil and Le Maire 2020)	2020
Spain	4	Electrolysis	Renewable	2030	(Spain 2020)	2020
Portugal	2.5	Electrolysis	Renewable	2030	(PRESIDÊNCIA DO CONSELHO DE MINISTROS 2020)	2020
Australia	23	Electrolysis	Solar-Wind-Hydro	2030	(Energy Council Hydrogen Working Group 2019)	2019
Netherlands	4	Electrolysis	Solar-Offshore Wind	2030	(Government of Netherlands 2020)	2020
Germany	10	Electrolysis	Wind- photovoltaics	2040	(German Federal Government 2020)	2020
Chile	25	Electrolysis	Solar-Wind	2030	(Chile 2020)	2020
European Union	40	Electrolysis	Renewable	2030	(EUROPEAN and COMMISSION 2020)	2020

In summary, Table 1 shows the meta-analysis studies on RES-based EROI, showing hydroelectric, wind and solar as the most efficient, with no risk. On the other hand, biomasses are considered very risky and biofuels unfeasible. The EROI values show great variability in the ranges established in the meta-analysis studies reviewed. Therefore, the risk categorization associated with the median value indicates the global potential of these energies, however, the specific conditions have to be analyzed within the context of each country, given that the EROI calculation depends on geographic conditions and other specific factors. (Walmsley et al. 2017).

Scope of GH_2 according to global strategies

Table 2 shows the main countries that have defined strategies focused on GH_2 production until 2020. Results show a convergence in terms of electrolysis as the technology that characterizes the conversion to H_2. In terms of energies, there is a consensus on solar and wind energy among those with the most ambitious plans in terms of capacity building, such as Chile, Australia, and Germany. However, within the European bloc, RES are generally referred to. The Norwegian government's strategic vision is that for H_2 to be a low- or zero-emission energy carrier, it has to be produced with zero or low emissions. It posits that this can be achieved by electrolysis of water using renewable electricity, or from steam reforming processes with natural gas or other fossil fuels combined with CCUS. In this strategy, low and zero-emission H_2 does not establish a specific position towards GH_2 production but rather to clean H_2 or simply H_2 (Norwegian Government, 2020).

Other countries such as the USA and Canada have an H_2 production agenda focused on various technologies, but recognize GH_2 as the one obtained by electrolysis and, despite highlighting hydroelectricity, wind and solar energy, they also include biomass and geothermal energy (Connelly et al. 2020; Government of the Russian Federation 2020; Natural Resources Canada 2020; HM Govermment 2021). One of the first policies among the countries leading the scientific production on the subject was the one from Japan, however, this focused on the promotion of H_2 use rather than its production, making it the potential first importer of this fuel (Japan 2017).

South Korea is committed to leading an ecosystem that integrates a public–private partnership with ambitious goals in the development and exploitation of H_2-related technologies (Stangarone 2020). Its overall strategy covers all stages of the H_2 value chain (i.e., including technologies related to the manufacture and use of H_2 vehicles, fuel cells for the transport and domestic sectors, H_2 transport and distribution systems, and commercialization).While also promoting efforts in H_2 production, it recognizes its limited production capacity, therefore it anticipates that 70% of consumption will have to be imported by 2040 (South Korean Ministry of Trade 2019). This makes the Japanese and Korean markets key international markets in the future configuration of the global H_2 trade.

Discussion

The concept of GH_2 appears to be a relatively fresh concept, as evidenced by its first appearance 25 years ago (US Department of Energy, 1995). The US Department of Energy report (1995) claims that H_2 produced by RES or nuclear energy would contribute to eliminating atmospheric pollution by carbon monoxide and ozone, and thus reduce global warming (US Department of Energy 1995). However, there is evidence from even earlier studies that address H_2 production from RES. For example, the use of wind in 1978 (Bilgen 1978) and solar in 1989 (Knoch 1989). In other words, it emerged much earlier as a method but without being identified with the term GH_2.

The current relevance of this energy vector responds to five aspects: Firstly, improvements in terms of efficiency of RES production processes (including production costs);

secondly, improvement in the efficiency and cost of electrolyzers (Laguna-Bercero 2012); thirdly, the need to capitalize on the surplus of RES production due to intermittencies (Clark and Rifkin 2006; Jensen et al. 2007; Hall et al. 2014; Brey 2021); fourthly, the great growth possibilities of these energies (ESMAP 2020); and fifthly, the strong impact on reducing CO_2 emissions that it may provide in the future (Yu et al. 2021).

As regards GHG, it should be noted that CO_2 emissions are not the only cause of concern from an environmental point of view. There are other polluting gases that directly affect the population and cause environmental emergencies in many cities, e.g. particulate matter (PM_{10}) and polluting gases such as ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) (World Health Organization 2005), being of special concern for certain types of RES, and especially in the case of some types of biomass.

According to Hosseini and Wahid (2016), environmentally friendly biomass is considered the best alternative fuel, potentially the major and most sustainable RES on the planet, with approximately 4,500 EJ of annual primary production (Hosseini and Wahid 2016). Nonetheless, biomass exploitation processes have significant shortcomings in terms of efficiency and emissions. For example, biomass has the lowest efficiency among RES for electricity production (30–35%), compared to solar and wind energy (achieving 40–60% efficiency) (Mohideen et al. 2021). It also presents other problems, such as ash, including silicate melt-induced slagging, alkali-induced slagging, corrosion and agglomeration (Niu et al. 2016). The adverse effects of biomass exploitation on ecosystem components rings alarm bells (Mai-Moulin et al. 2021). Another form of biomass exploitation is bio-hydrogen or H_2 produced biologically from biological waste, wastewater, forestry and agricultural residues, among others (Osman et al. 2020a). This method does not have the shortcomings of biomass burning in terms of emissions. However, if we consider the low EROI values for biofuels, it can be established that they have less potential to produce GH_2 than other RES, even compared to other RES of the same biomass family (see Table 1), in this case biomass (Physical process) being the one with the highest potential.

In general, the aim of promoting GH_2 production is to achieve a RES based energy carrier at a competitive cost with respect to traditional fuels, which contributes to solving GHG emissions. In this sense, biomasses also present fewer benefits compared to the rest of RES. According to results of a recently published study by Gemechu & Kumar, they show that the CO_2 values of wind based water electrolysis ($0.69 \pm 0, 04$ kg CO_2 eq / kg H_2) on average has values three times lower than the best result for H_2 produced from a biomass (the case of bio-oil reforming varying between 1.57 and 3.46 kg CO_2 eq / kg H_2), and in the case of supercritical water gasification (SCWG) of algal biomass, this could increase between 10.14 to 12.72 kg CO_2 eq / kg H_2 (Gemechu and Kumar 2021). Although the above elements lead us to question whether this RES can be classified as green, the keyword map indicates that biomasses and biogas have been classified as GH_2, with several recent examples (Di Marcoberardino et al. 2018; Preuster and Albert 2018; Cholewa et al. 2018; Akroum-Amrouche et al. 2019; Minutillo et al. 2020; Gonzalez Diaz et al. 2021; Zhao et al. 2021), and especially bio-hydrogen, a trend which has been gaining ground (Abuşoğlu et al. 2017).

As regards to nuclear energy, although the US department of energy (US Department of Energy, 1995) raised this energy source in the conceptualization of GH_2, in our results it only appears in the keyword maps for SH_2 (Fig. 6) and RH_2 (Fig. 4). In any case, the appearances on the RH_2 map refer to the context where RES and nuclear energy are integrated to produce H_2. (Orhan et al. 2012; Orhan and Babu 2015; Agyekum et al. 2021; Temiz and Dincer 2021). Although nuclear energy cannot be included in the RES and green energy framework, it is called "clean energy[5]" because no GHGs are emitted during the process of generating electricity from this source (Velasquez et al. 2021; Elshenawy et al. 2021; Brown 2022; Hassan et al. 2022). This, together with its efficiency levels, has led several authors to consider it as a sustainable option for the production of H_2 (Dincer and Balta 2011; Dincer and Zamfirescu 2012; Zhiznin et al. 2020; Velasquez et al. 2021). There are a wide range of scientific papers on H_2 production using nuclear energy, and it seems that plans for H_2 production stimulate the development of the symbiosis of nuclear energy and RES (Zhiznin et al. 2020). In any case it should not be forgotten that this energy source is enormously controversial due to its drawbacks in terms of perceived safety (Prati and Zani 2012; Perko et al. 2018; Deng et al. 2018), waste treatment (Ewing et al. 2016; Yano et al. 2018), and geopolitics (international political conflicts and lack of massification towards underdeveloped countries[6]) (International Energy Agency (2021); Hickey et al. 2021). These elements may somewhat contradict certain sustainability criteria under the Sustainable Development Goals (SDGs) and the Paris Agreement(UNFCCC 2015; United Nations 2015). It is important to note that among the strategies reviewed, no nation was identified as considering nuclear energy for GH_2 production.

[5] Without considering the mining processes.

[6] There are currently more than 400 reactors of this type in 30 nations, generating approximately 11% of the world's electricity (Internacional Atomic Energy Agency).

Table 3 Proposed criteria for the use of the terms GH_2, SH_2 and RH_2. *Source*: Own elaboration, 2022

Concept	Energy Type	NEA	CO_2 emissions*	Other emissions*	Community relations
GH_2	RES	e.g. EROI pou: no risk; < 10–15: 1 or low risk < 5–10: 1	Low emissions	Emissions-free	Well valued by the community
SH_2	RES alone or combined with other fuels	e.g. EROI pou: no risk; < 10–15: 1 or low risk < 5–10: 1	Reduction of emissions compared to state of the art	Reduction of emissions compared to other sources	Improved community acceptance
RH_2	RES	Any value	Any value	May emit, e.g. particles, ashes, odors, etc	Sometimes they can generate conflicts within the community (e.g. big scale projects; biomass from wast…)

*Those emissions produced in the manufacturing process of renewable energy systems and equipment have not been considered

According to the cited SDGs, sustainable development can be summarized as development that meets current needs without compromising future capabilities (United Nations 2015). The SDG 7 goal include access to energy, the incorporation of RES and improvement of energy efficiency, among others. This has given rise to three narrative imperatives that sustainable development must meet: satisfying human needs, guaranteeing social justice, and adhering to permissible environmental values (Holden et al. 2021). Among the indicators for defining sustainability, despite no single acceptance of such, in general they point to economic, technical, environmental, social and political factors (Mai-Moulin et al. 2021; Gunnarsdottir et al. 2021; Saraswat and Digalwar 2021). Therefore, we believe that the use of the term "SH_2" is correct when referring to improvements in economic, technical, environmental, social, and political factors that occur in H_2 related processes, as long as the improvement in one factor is not to the detriment of other factors.

National global strategies show clear signals on the use of energy sources and the technology to be employed in global GH_2 strategies (see Table 2). Electrolysis is the main conversion technology, as evidenced by the fact that future capacities are projected in electrolyzer capacity (in GW). On the RES side, countries with a clear focus on GH_2 production have clear targets for the use of solar and wind energy. Accordingly, the GH_2 concept could be defined as H_2 obtained from RES, using electrolysis, free of polluting emissions that guarantee an energy return that does not jeopardize its sustainability. In some cases (e.g. in Portugal and Spain), it is stated that H_2 could also be produced from biomass (i.e., through gasification processes, biochemical conversion, or biogas reforming), as long as sustainability requirements are met. Both countries also express their H_2 production targets in electrolyzer capacity (in GW) (Spain 2020; Presidência Do Conselho De Ministros 2020).

There are also other factors in the H_2 production chain that may jeopardize its sustainability. On one hand, there are the losses in the electrolyzers. In this sense, review investigations that consider the performance of electrolyzers and the specific phenomena that occur in their components are very useful for present and future research (Falcão and Pinto 2020). On the other hand, it is essential to consider the scale of the envisaged projects, which directly conditions aspects such as H_2 storage and transport, also including local community acceptance. The following projects, which are reproducing traditional centralized energy models (i.e., large-scale projects), could be used as example: i) The "green crane" project, under public–private partnership. This project, headed by the Spanish Enagas and the Italian ESNAM gas transmission companies, under which umbrella the "green spider" project seeks to launch a €2,250 million investment plan to turn Spain into an H_2 exporting country to north Europe (Enagás 2022); or ii) The case of Chile, for example, where the areas of greatest wind and solar energy potential are located in the south (Magallanes Region) and north (Antofagasta Region) respectively (Chile 2020), while the largest population and business activity are located in the center of the country (Santiago de Chile), i.e., at a distance of more than 500 km.

In general, we consider the timely monitoring of research indexed under the terms electrolyzers, H_2 storage, H_2 distribution and transport, and especially the EROIpou for H_2, to be essential. As stated by Zamani et al. 2022, surveillance of emerging issues is fundamental to the work of researchers, practitioners, and policy makers. At the same time, the need to provide more organized information in order to facilitate the transfer of knowledge to decision-makers in technological fields is indispensible (Garechana et al. 2022). It is also important to bear in mind that this knowledge is a key input for tracing technological trajectories, determining when a technology has matured, identifying existing knowledge gaps in these areas, and learning about new emerging knowledge (Alvarez-Meaza et al. 2020; Zamani et al. 2022).

From a technical–economic, environmental, and social perspective, we believe it is important to make a proposal that facilitates the appropriate use of the terms GH_2, SH_2 and RH_2. To this end, we propose five criteria: the type of energy, estimated EROI values, CO_2 emissions, other types of emissions, and the community's perception of the type of project. These were categorized in correspondence with the insights gained during this research (see Table 3). Failure to meet at least one of the criteria is sufficient not to reach the green category, therefore, it would fall between the sustainable or renewable category. Note that the renewable category is the least restrictive; its only condition is to use RES. Sustainable, on the other hand, necessarily implies that improvements will occur, at least in relative terms.

As the ultimate expression of technological progress, GH_2 should represent the cleanest form in terms of emissions. Therefore, it is not enough to use RES to classify a production method as green; it is also essential to evaluate the type of energy, the GHG emissions of the production process, the production technologies used (Dawood et al. 2020; Velazquez and Dodds 2020) and the carbon footprint of the supply chain, as well as including a NEA based on indicators such as EROI or EPBT.

Conclusions

The great expectations created around H_2 use as an energy vector focus the attention of the scientific community. This is demonstrated by the exponential growth in the number of publications on the subject. Researchers play an essential role in providing the community with knowledge of high scientific value, becoming fundamental referents in the most complex challenges facing humanity. The literature produced becomes the basis for projects of the greatest technological complexity, as well as for the formulation of new policies. For this reason, it is of utmost importance to be careful about the indexing and use of terms that can be transferred to society. In the case of the use of the indexing terms "GH_2, RH_2 and SH_2" as synonyms, this could lead to the acceptance of technologies that do not meet the standards to be classified within each term.

The most relevant authors as regards the H_2-related production, distribution and technologies belong to developed countries, which are also the ones that provide the majority of funding for this type of research. Connecting with these researchers may help foster innovation in solutions that address local priority challenges and accelerate the implementation and transfer of these technologies, responding to the commitment made by Paris Agreement signatory countries and also in line with SDG 7 (United Nations 2015), which propose increasing international collaboration to enable access to clean energy research and technology. In this sense, more developed countries should favor the financing of those research projects on GH_2 production that include the participation of organizations and researchers based in these less developed countries that have a high potential for RES generation due to their natural conditions.

The term "ecological H_2" has been used very rarely and, according to its trend, it is not expected to gain relevance in the coming years. The term clean H_2 shows a discrete record, however its relevance may be favored by the development of blue hydrogen and H_2 produced from nuclear energy. As regards the term RH_2, it has a broader scope than GH_2 and may include studies on biomass or other RES for H_2 production methods that are not totally clean or efficient, with low EROI values. Unlike in the RH_2 map, in the GH_2 map there is little use of the terms linked to certain RES such as solar and wind, while the terms "biomass" and "biofuels" are much more prominent. Research on GH_2 is growing exponentially, however, its growth rate is lower than for SH_2 and RH_2. This is partly because there has been no standardization in the use of these terms. Since there is no delimitation or understanding of the terms sustainable, renewable and green, articles can be framed in any of them, under the assumption that they are synonyms.

Production, distribution, and consumption of GH_2 is a highly complex, diverse subject given the great variety of technologies and the specific characteristics of each RES according to the conditions of each country. In this sense, it is important to promote studies that analyze H_2 efficiency levels, as well as to disseminate studies of implemented cases associated with different international experiences that help to generate maturity and investor confidence in order to accelerate massification in the production of this energy carrier, also achieving the incorporation of medium and small actors in the implementation of national policies. Therefore, it is fundamental to promote the correct identification of keyword indexing terms among scientific editors and authors.

As the ultimate expression of technological progress, GH_2 should be a reference for technologies that meet the acceptance criteria by the scientific community, the highest standards in terms of emissions and efficiency. In addition to the use of RES to classify it as GH_2, it is essential to evaluate the type of RES, the production technologies as well as the carbon footprint of the supply chain, also including a NEA based on EROI, EBPT, or other related indicators. In turn, it is important to influence the vision of policy makers to confer a special status to GH_2. Therefore, the new policies formulated would aim for H_2 production models to apply for the "green" distinction, to be favored by the incorporation of incentives, possibly fiscal or commercial (tariff reduction), among others. Nonetheless, one should not be absolute when defining the type of technologies used due to the rapid development and production of new techniques. At present electrolysis and/or photoelectrolysis are the ones being used in national H_2 strategies, to the point that they project their objectives referring to the installed capacity of electrolyzers (in GW). Although several authors describe certain types of biomass as very promising, we consider that any strategy for GH_2 production based on these RES should pay special attention to the efficiency levels achieved in the different processes and how to control or mitigate the resulting waste and pollutant emissions.

Main national policy strategies have included the H_2 as the most promising energy carrier towards the energy transition path. In any case, the relevance of big scale projects should also be underlined. In this regard, indicators such as EROIpou may become fundamental to classify projects as RH_2 or GH_2, as well as to guide different national strategies towards a low carbon transition. Despite the fundamental progress made in estimating the EROI of different technologies (e.g., as regards the use of Integrated Assessment Models (IAMs) that allow the EROI to be estimated endogenously and dynamically), the fact that the different meta-analyses do not differentiate between different EROI metrics (e.g. EROIpou; EROIext…) is a clear sign of the necessity to establish clear boundaries and improve the methodological aspects as regards this indicator. Moreover, the present study also reveals that despite EROI being now well-established within the scientific community for evaluating different energy projects, it is at very incipient stage when it comes to evaluate projects related to H_2, especially GH_2. In any case, as Carbajales-Dale states, we consider that the moment has come for policy makers to make greater use of this fundamental tool in determining their overall long-term energy strategies towards energy transition (Carbajales-Dale et al. 2014). In this sense, EROI is a complex metric that, together with other indicators (e.g., LCA), may be fundamental in order to distinguish boundaries between GH_2, RH_2 and SH_2.

This work shows the main challenges from the point of view of indexation in relation to the types of energy used for the production of GH_2. However, other aspects such as the energy loss in electrolyzers, storage, scale of the projects, transport, different technologies and RES used for its production, also including different forms of H_2 consumption and the aspects related to community acceptance, should be studied further. Furthermore, future research should focus on the analysis of EROI boundaries and its different modalities (i.e., EROIpou, EROIext…), which are useful tools to evaluate the efficiency of each of the stages of the H_2 chain. We should also address the use of biomasses as an energy source for the production of RH_2, remarkable for the wide variety of existing materials and technologies for its exploitation. Accordingly, the application of bibliometric tools combined with sustainability indicators can be very useful for providing synthesized information to environmental policy makers and stakeholders in general.

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Author contribution All authors contributed to the conception and design of the study. Material preparation, data collection and analysis, and manuscript writing were performed by Willmer Guevara, Itziar Martínez, and Rosa María Río-Belver. All authors read and approved the final manuscript.

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Availability of data and materials The datasets used and/or analyzed during the current study are available from the corresponding author.

Declarations

Ethics approval and consent to participate Not applicable.

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