Green Hydrogen European Perspectives. Insights from Bibliometric Analysis

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Abstract. *Hydrogen is currently mainly obtained from fossil resources, and the associated CO_2 emissions in the current production process are very high (10-20 kg CO_2 /kg H_2). Given its importance as an energy source and for storing excess electricity, new methods for producing hydrogen with low carbon emissions are being explored. The most widespread approach is the electrolysis of water using renewable energy sources.*

In recent years, numerous bibliometric studies have focused on hydrogen. The present study aims to analyse the scientific community's perspective on new technologies for hydrogen production with minimal environmental impact, using a systematic bibliometric approach. European trends on green hydrogen were examined for the period 2020-2024, using Web of Science database, the main tag "Green hydrogen production" and secondary tags such as "European Green Deal", "leveled cost of hydrogen" and "clean hydrogen".

The exported data was processed using bibliometric analysis tools to identify key terms, cluster formation, and interconnections between concepts. The correlation analysis highlights several key findings:

- *The essential contribution of hydrogen in achieving a sustainable and decarbonized energy future.*
- *The development of efficient, scalable and sustainable systems depends on innovative green hydrogen production processes.*
- *The interconnection of biomass with other terms in Cluster 4 emphasizes its central role in promoting renewable energy technologies.*

This study contributes to the current literature by providing a comprehensive analysis of research trends and scientific perspectives on green hydrogen production, supporting future advances in this field.

Keywords: green hydrogen, European Green Deal, sustainability, performance, biomass.

Introduction

The global transition towards a sustainable energy system has highlighted the importance of hydrogen in the decarbonisation process, especially in sectors where emissions are hard to reduce. Green hydrogen involves the use of renewable energy in the water electrolysis process and has

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attracted considerable interest due to its potential to significantly reduce greenhouse gas emissions. Projections for 2050 show the key role of green hydrogen in achieving climate neutrality goals, supported by technological advances and the decline in the costs of renewable energy sources (IRENA, 2022).

Within the 17 Sustainable Development Goals (SDGs) of the UN 2030 Agenda (European Commission, 2015), SDG 7, which aims to ensure access to affordable and clean energy for all, aims to contribute to combating climate change by promoting clean energy technologies. The European Union (EU) has developed various policies to reduce energy consumption and ensuring sustainable energy sources for Europe.

Based on the European Green Deal, climate neutrality has been set as an objective to be achieved by 2050 (European Commission, 2019). Thus, the energy sector in the European Union, which generates more than 75% of greenhouse gas emissions (European Commission, 2019), needs to undergo a significant transformation. The transition involves improving energy efficiency, electrification of the energy system, development of renewable energy production, carbon capture and storage, use of alternative fuels and the integration of hydrogen as a major energy vector (European Commission, 2018). The use of alternative fuels represents a sustainable long-term strategy that brings both environmental and economic benefits, contributing to the transition towards a greener and more energy-efficient society (Măcinic et al., 2024).

Green hydrogen enables energy storage and fulfils the role of clean energy carrier, thus contributing to sectoral integration into a unified energy market by converting electricity into chemical energy (Schiebahn et al., 2015).

Green hydrogen technologies have considerable potential in the transition to a low-carbon global economy. This type of hydrogen, generated by using renewable electricity to power electrolyzers that split water into hydrogen and oxygen, is seen as a sustainable solution for the decarbonisation of energy-intensive sectors such as transport, heavy industry and energy storage (IRENA, 2022). The EU, through initiatives such as the European Green Deal and the 2020 European Hydrogen Strategy, is playing a leading role in promoting this energy vector, setting ambitious targets for increasing production capacities and the necessary infrastructure (European Commission, 2020).

In addition to the climate objective, green hydrogen contributes to increasing Europe's energy security. The COVID-19 pandemic and recent geopolitical changes have highlighted the need to reduce dependence on fossil fuel imports and diversify energy sources, especially in the Central and Eastern European regions. Recent projects such as Hydrogen Valleys and funding through Horizon Europe and the Innovation Fund demonstrate the EU's active involvement in promoting collaboration between research, industry and public policies.

Bibliometric analysis is an important method for mapping and quantifying scientific research, essential for understanding the dynamics of evolution in the field of green hydrogen. This method provides valuable information on emerging trends, international collaborations and centers of excellence in the field. Recent studies show a significant increase in the number of works in this field, with a strong concentration in Europe, Asia and North America.

This article aims to analyze the scientific community's vision on new techniques for obtaining hydrogen with minimal environmental impact, through a systematic bibliometric approach, identifying academic contributions and their impact at a global level. The analysis will examine the volume and distribution of research, key actors from academia and industry, and emerging research areas. Through this approach, the study contributes to a better understanding of Europe's role in developing a green hydrogen economy.

Literature review

Recent numerous studies have focused on the technological, economic (El- Emam & Ozcan, 2019, Kar, Harichandan, & Roy, 2022) and geopolitical aspects of large-scale clean hydrogen production (Lebrouhi et al., 2022). One of the major findings is that countries are likely to adopt distinct roles in the global renewable hydrogen market, depending on the renewable energy resources, water reserves and infrastructure they possess or can develop (Pflugmann & De Blasio, 2020). Recent estimates of the global potential of renewable hydrogen (Fasihi et al., 2021) and production costs (Martínez de León et al., 2022) support this conclusion.

Some countries from EU have a high export potential for low-emissions hydrogen, possessing resources in excess of estimated domestic demand (the case of Spain), but no member state is likely to become a global leader in hydrogen exports (Pflugmann & De Blasio, 2020).

Interest in international trade in renewable hydrogen is growing, given that certain countries will be able to produce hydrogen more and more cheaply than others (IRENA, 2022).–Direct photoelectrolysis of water using photo-anodes can be improved by combining them with photovoltaic cells. (Schoonman & Kroll, 2011)

Green hydrogen production technologies

Green hydrogen production is based on the electrolysis of water powered by renewable energy sources such as solar, wind and hydropower. The increase in electricity production from variable sources such as wind and photovoltaics has opened up new perspectives for the use of green hydrogen. However, these renewable sources present challenges such as imbalances between energy production and consumption requirements.

Water electrolysis uses electricity from renewable sources with minimal CO2 emissions. The already known hydrocarbon technologies will be complemented by CCUS (carbon capture and storage) systems. These two will be the main technologies for “low-emissions hydrogen”.

Globally, 71% of hydrogen is produced by steam reforming of natural gas, a mature and cheap method, but based on fossil resources. However, electrolysis is becoming increasingly competitive due to the temporary surplus of electricity from renewable sources. One aspect of implementing new technologies is the financial costs, since the production price of green hydrogen is significantly higher than that produced from natural gas (Antony et al., 2018).

Obtaining hydrogen by biological processes (e.g. using the purple sulphur bacteria Thiocapsa roseopersicina) allows for mild operation, high selectivity and the use of renewable sources, but the conversion efficiency is low and the costs of using photobioreactors are high. (Harai et al, 2010)

Uses of hydrogen

The potential to reduce carbon emissions and contribute to the integration of renewable energy sources, allow the use of hydrogen in extremely varied fields (transportation, obtaining clean energy, storage, conservation and reduction of energy consumption) (Zhou et al., 2022).

Most carbon emissions are generated by transportation. Hydrogen-powered vehicles, such as hydrogen fuel cell electric vehicles (FCEVs), use hydrogen in fuel cells to produce electricity, with the only byproduct being water. The advantage over traditional electric vehicles consists in greater autonomy and reduced recharging time. In addition, hydrogen technology can be extended to include buses, trucks and trains, providing a solution for public transport and long-distance freight transport without contributing to air pollution.

Hydrogen can also be used to generate electricity by directly converting stored energy into chemical energy, the main advantage being the non-generation of greenhouse gas emissions. Hydrogen can be produced from renewable sources (such as solar or wind energy) through electrolysis, and the stored energy can be used when renewable sources are not available, thus contributing to the stabilization of electricity grids.

Hydrogen also plays a significant role in energy storage, a key technology for integrating intermittent energy sources. It can then be used in power plants or converted into synthetic fuels for transportation.

Hydrogen is already widely used in industries such as oil refining and ammonia production, being an important agent in chemical processes. However, the use of "green" hydrogen represents an important step in the decarbonization of the industry. Hydrogen can also play a significant role in the production of steel and cement, where CO2 emissions are significant, replacing traditional processes that use fossil fuels with the aim of reducing emissions into the atmosphere and environmental degradation given the multitude of sources from which carbon comes (Enache et.al, 2024).

In conclusion, hydrogen can be used as a fuel in transportation or for energy production, but also in various classic chemical processes (obtaining methanol, ammonia, etc.) and in innovative processes that also consider the conversion of CO2 from the atmosphere (Simion et.al, 2023).

Methodology

Science database was bibliometrically processed using the VOSviewer application (version 1.6.20.). The main search tag, "Green hydrogen production" was completed with 3 additional labels (”European Green Deal”, ”levelized cost of hydrogen ” and ”clean hydrogen”) for capture the aspects at European level regarding the efficiency of the process and costs. Also, when applying the existing filters in the mention platform, we aimed to capture open access information, updated information and articles edited by European authors. The filters used were: “European States", "Open access" and "publication years 2020 -2024" Thus, following this sequence of labels and filters, the bibliometric analyses will consider 2663 articles.

Principles of bibliography and statistical bibliography underlie bibliometrics. The analysis of all important aspects of the researched phenomena can be hindered in a bibliometric analysis for the following reasons: large volume of information, filters and tags that eliminate articles with important content, high consumption of time and resources to perform a good bibliometric analysis that encompasses the whole knowledge structure specific to a research area. Other aspects of green hydrogen can be obtained by analysing specific data (article title, keywords, abstract, country of origin of the authors, connections between articles).

The first step was the analysis based on publication years and Web of Science categories.

To capture aspects and correlations we used art software by applying co-occurrence filters, author keywords, minimum 15 co-occurrences. Resulting in 4 clusters on which we highlighted the links between the word/expression with the highest frequency and its connection with the other elements in the cluster.

Results and discussions

Because the authors wanted to capture trends at European level regarding green hydrogen, the establishment of the scientific articles base from the Web of Science database on which the biometric analysis will be performed was carried out by querying the main tag " Green hydrogen production” and secondary labels ”European Green Deal", "levelized cost of hydrogen", and "clean hydrogen”, obtaining the following evolution of the number of items in the sample (Table 1):

Table 1 Number of items according to the label used

Filter applied (Keyword)	Articles number in the selection
”Green hydrogen production”	5.163
”European Green Deal”	20.806
”levelized cost of hydrogen"	21.053
" clean hydrogen"	22.312

Science database (accessed 20.01.2025).

In order to identify the current issues on the European area, the authors used consecutively the following filters: authors of the articles - European, access -Open, period of the research - last 5 years. The query results are presented in Table 2:

Table 2 Items identified by applying filters

Filter applied	Number of articles after applying filter
Articles written by authors from Europe	5.163
Open Access	3.090
Publication period 2020-2024	2.663

Science database (accessed 20.01.2025).

Bibliometric analyses will be performed on the 2663 scientific articles using specific Web of Science filters and the VOSviewer application.

The theme chosen for the research in the present article is topical, a conclusion drawn from the growing interest of researchers in this topic addressed in an increasing number of researches each year (Table 3).

Table. 3 Annual distribution of articles

Year of publication	2020	2021	2022	2023	2024
Number of articles	221	371	581	669	821

Science database (accessed 20.01.2025).

In order to make it easier to visualize the specific steps of the present research, the choice of selections and the exclusion of different categories of articles, so that any reader of the article can quickly understand the meaning of the review carried out, in figure number 1 we have presented the PRISMA 2020 flow diagram for the systematic review of searches in the Web of Science database, so that the effects of applying specific filters are understood.

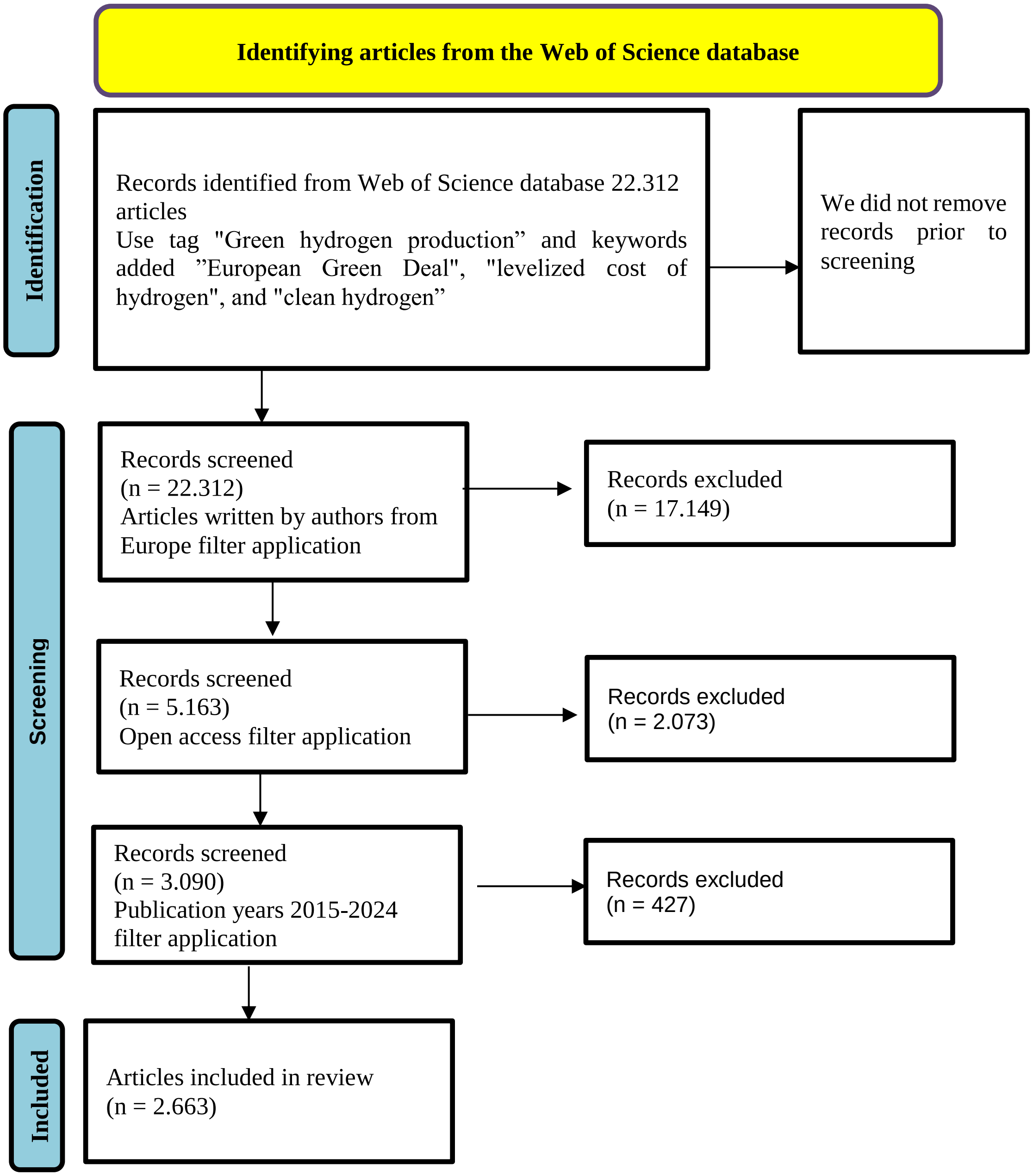

Figure 1 PRISMA 2020 flow chart for applying filters from the Web of Science database

Source: Made by the authors using the PRISMA 2020 diagram.

Articles were excluded only through the specific filters of the Web of Science database, the authors not intervening in the selections of the database. Applying a filter selection was done on the database of the previous filter

In figure number 2, we analyzed the membership of the articles in the selection to the Web of Science categories and from the distribution we see that the main categories are those specific to green hydrogen.

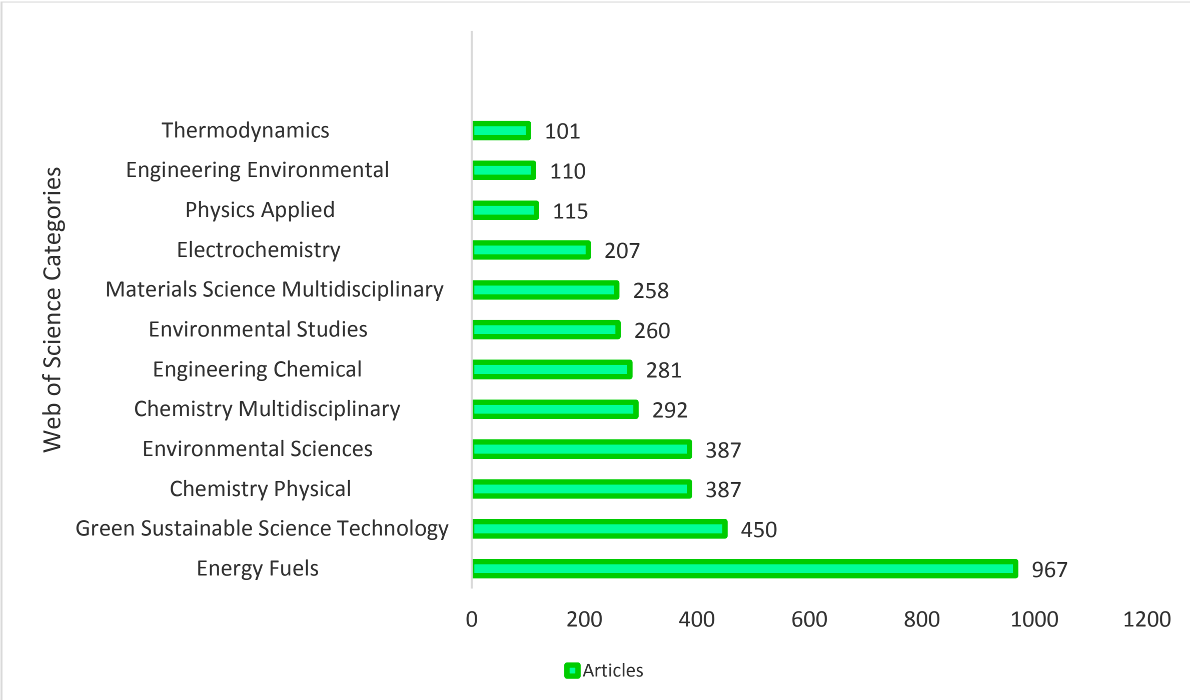

Figure 2. Web of Science categories

Science database (accessed 20.01.2025).

The VOSviewer program allowed the analysis of the 2663 selected articles in terms of the density of phrases or words used.

By applying the co-occurrence filter, for all keywords with a minimum of 15 occurrences, only 196 (out of the 11.183) words/phrases analysed met this criterion. The highest density is recorded by the words: hydrogen, green hydrogen, energy, performance, storage, renewable energy, hydrogen - production, biomass, European Green Deal. From the analysis of the content of the predominant phrases in this analysis we can conclude that the articles in the selection deal with. The ranking of words by total link strength resulting from VOSviewer is shown in Table 4.

Table 4. Link strength between articles analysed by Keyword

No.	Keyword	Occurrence	Total link strength
1	hydrogen	373	1626
2	GREENE hydrogen	282	1226
3	energy	230	1167
4	performances	207	959
5	storage	167	930
6	Renewable energy	170	777
7	hydrogen - production	173	707
8	biomass	116	530
9	European Green Deal	222	466

Source: Own conceptualization, processing of WOS data with VOSviewer software.

The graphic representation of the grouping into the 4 clusters and the density proportional to the size of the words/phrases is represented in figure number 3. Thus, the connections between words/phrases in each cluster are visible.

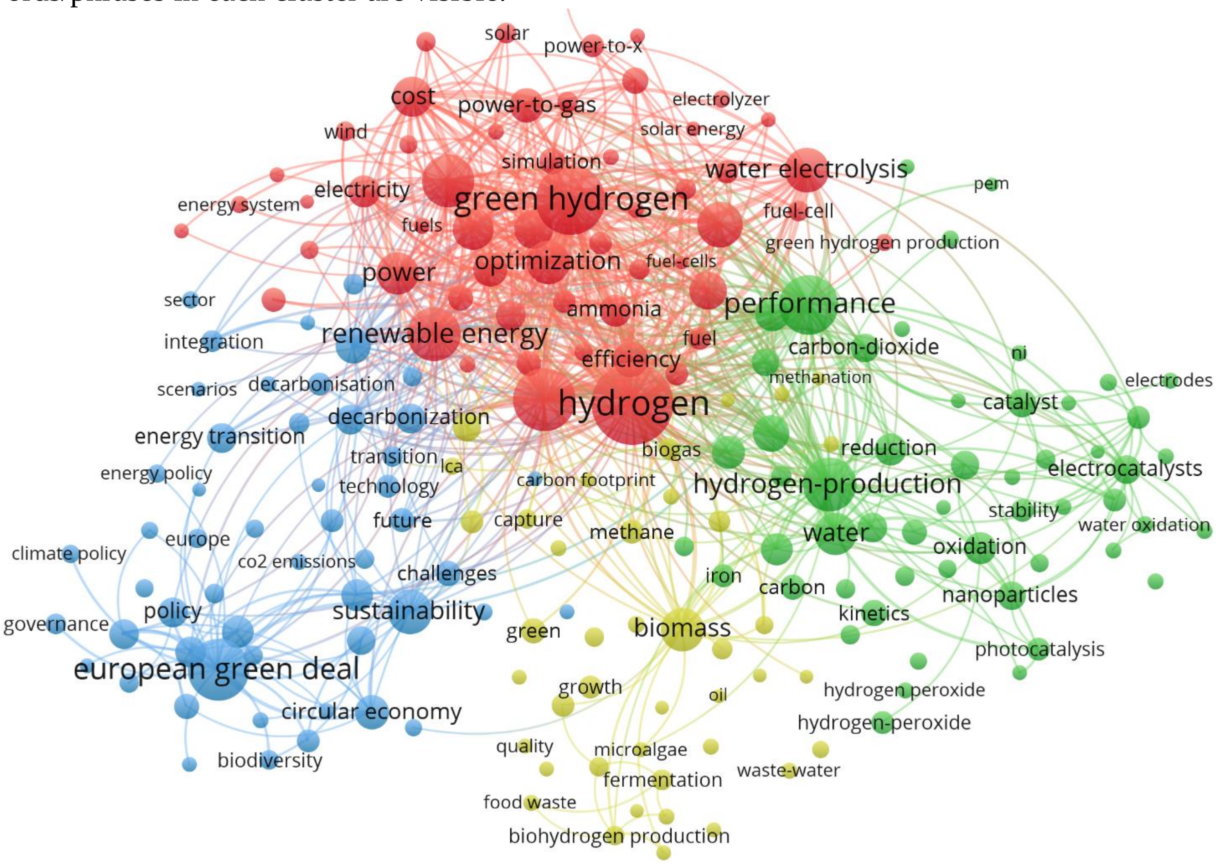

Figure 3. Phrase and word density of the 196 words that have at least 15 co-occurrences

Source: Conceptualization own accomplished through the software VOSviewer.

After identifying those 196 occurring keywords with a frequency of occurrence of at least 15, they were grouped into 4 clusters (sets of items belonging to a bibliometric map) using VOSviewer, presented in Table 5. An article can be assigned to only one cluster or belong to none.

Table 5 Clusters with related colors

Cluster 1 (53 items)		Cluster 2 (51 items)	
ammonia	hydrogen	carbon	hydrogen production
battery	levelized cost of hydrogen	carbon dioxide	hydrogenation
CO2 capture	exemplary	catalysis	ironically
combustion	natural gas	catalysts	kinetics
cost	operation	cells	mechanism
cycle	optimization	co2	methanol
design	plant	conversion	nanoparticles
efficiency	power	decomposition	nanosheets
electricity	power-to-gas	degradation	us
electrolysis	power-to-x	efficiently	nickel
electrolyzer	reanalysis	electrocatalysis	nitrogen
energy	renewable energy	electrocatalyst	oxidation
energy storage	renewable energy source	electrocatalysts	oxides

Cluster 1 (53 items)		Cluster 2 (51 items)	
energy system	simulation	electrodes	oxygen
energy storage	solar solar energy	evolution	oxygen evolution
exergy	storage	formic acid	reactive oxygen species
feasibility	supply chain	generation	tree
fuel fuel -cells	system	green chemistry	performances
gas	techno economic analysis	green synthesis	photocatalysis
green ammonia	techno-economic analysis	h-2 production	reactor
green hydrogen	techno-economic assessment	hydrogen evolution	reduction
green hydrogen	technology	hydrogen evolution	stability
production	transport	reaction	tio2
heat	transportation	hydrogen peroxide	water
hydrogen storage	water electrolysis	hydrogen production	water oxidation
infrastructure	wind	hydrogen peroxide	water splitting
Cluster 3 (51 items)		**Cluster 4 (41 items)**	
agriculture	European Union	acid	methanation
biodiversity	framework	anaerobic digestion	methane
bioeconomy	future	bacterium	microalgae
bioenergy	governance	behavior	state-of-the-art
carbon capture	green deal	biogas	oil
challenges	hydrogen economy	biohydrogen	pretreatment
circular economy	impact impacts	biohydrogen production	products
atmosphere	indicators	biomass	pyrolysis
climate change	industry	biomass gasification	quality
climate policy	innovation	biomethane	recovery
climate-change	integration	biorefinery	removal
CO2 emissions	just transition	capture	renewable hydrogen
common agricultural	management	carbon footprint	syngas
policy	policy	dark fermentation	temperatures
consumption	prediction	ethanol	waste
decarbonization	Scale	fermentation	wastewater
decarbonization	scenarios	food waste	
economy	section	gasification	
electric vehicles	strategies	GREENE	
emissions	support	green energy	
energy efficiency	sustainability	growth	
energy policy	sustainable development	Ica	
energy transition	systems	life cycle assessment	
EU Europe	technology	life cycle assessment	
European Green Deal	Transitional	lignocellulosic biomass	

Source: Own conceptualization, data processing with VOSviewer (accessed on 20.01.2025).

In order to analyse specific aspects of the topic addressed in the present article the authors analysed both inter-cluster and intra-cluster links. For each cluster we selected the word with the strongest links (Table 6):

Table 6. Words with stronger links within the cluster

Cluster	Word	Link strenght	Figure number
1	" hydrogen”	1626	3
2	“performance”	959	4
3	"European green deal"	466	5
4	“biomass”	530	6

Source: Own conceptualization, data processing with VOSviewer.

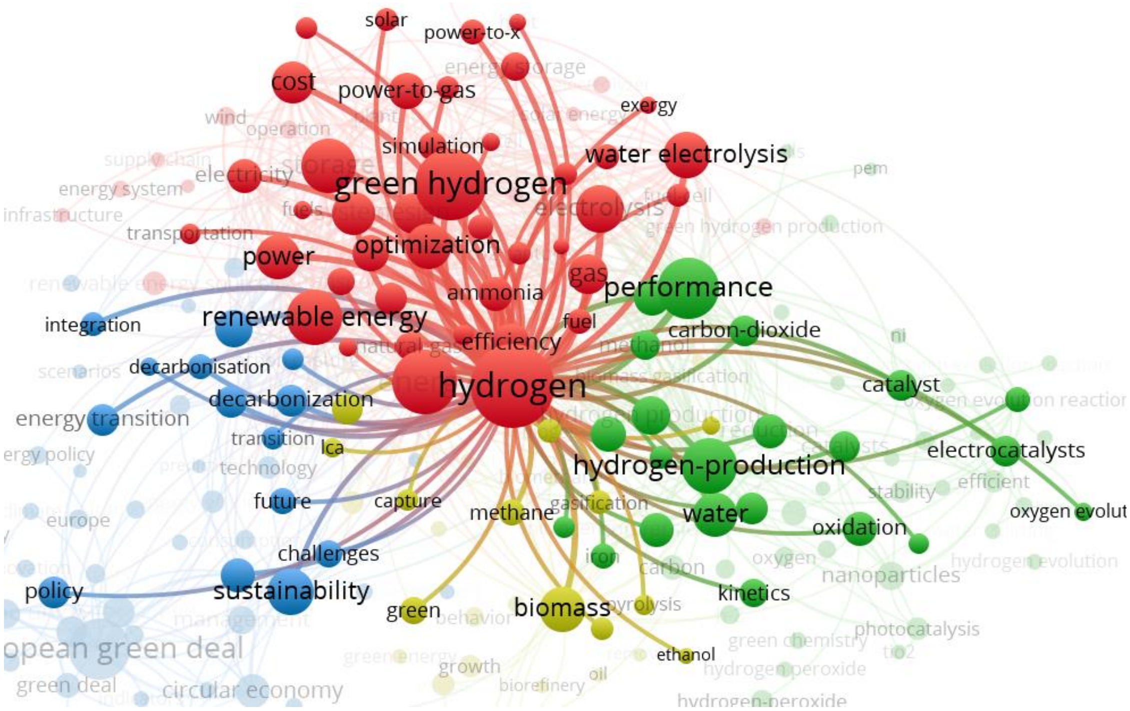

Figure 4. " Hydrogen " (Cluster 1)

Source: Own conceptualization made with VOSviewer software.

Within cluster 1, we identify several hydrogen bonds with various categories of notions grouped within the cluster but also with other clusters as follows:

- *renewable energy* (solar, wind, renewable energy, renewable energy source). Hydrogen is often produced using renewable energy through water electrolysis, were electricity from solar or wind energy splits water into hydrogen and oxygen. This process generates green hydrogen, which is carbon-free;
- *storage* (energy storage, hydrogen storage, battery). Hydrogen serves as a long-term energy storage solution, complementing technologies such as batteries that are suitable for short-term storage. Hydrogen storage involves either compression, liquefaction, or chemical binding in materials such as ammonia;
- *fuel cells* (fuel, fuel cells). Hydrogen is a primary fuel for fuel cells, which convert hydrogen into electrical energy through an electrochemical process, which is crucial for transportation and stationary power systems;
- *ammonia* (ammonia, green ammonia). Green ammonia is synthesized by combining green hydrogen with nitrogen. Ammonia acts as a carrier for hydrogen, allowing for easier transportation and storage, especially for international energy trade;
- *efficiency* (efficiency, optimization). The production and use of hydrogen systems involve optimization challenges to maximize efficiency and minimize energy losses;
- *economics* (cost, techno-economic analysis, levelized cost of hydrogen). The viability of hydrogen technologies depends on reducing the levelized cost of hydrogen (LCOH). Techno - economic analysis is used to assess the financial feasibility and market competitiveness of hydrogen systems compared to conventional energy systems;

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- *CO_2 capture* (CO_2 capture, natural gas). Hydrogen production can be linked to CO_2 capture in processes such as blue hydrogen, in which natural gas is reformed to produce hydrogen while capturing the resulting CO_2 emissions;
- *infrastructure* (infrastructure, supply chain). Developing a robust infrastructure and supply chain is crucial for the efficient production, storage and distribution of hydrogen. This includes pipelines, storage facilities and refuelling stations.
- *energy systems* (energy system, power - to -gas, power - to -x). Hydrogen integrates with energy systems through power - to -gas or power - to -x technologies, in which surplus renewable electricity is converted into hydrogen or other energy carriers;
- *feasibility* (design, simulation, modelling). The implementation of hydrogen projects requires advanced design, simulation and modelling to achieve new performances.

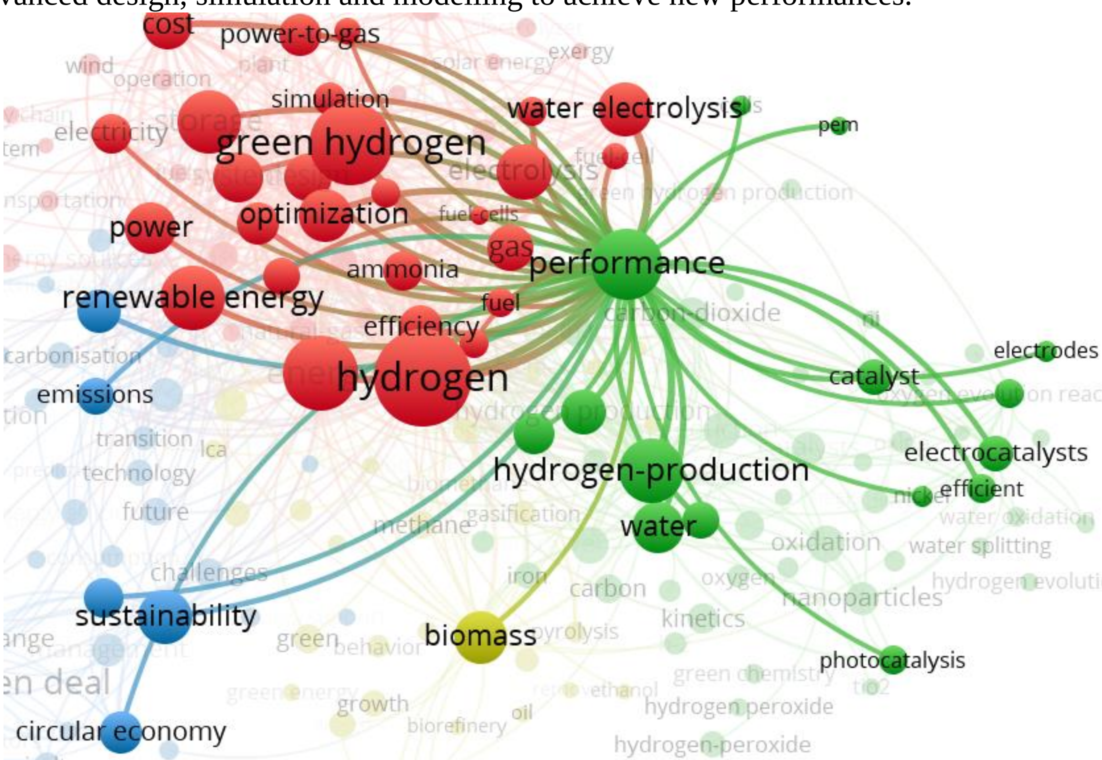

Figure 5. "Performance" (Cluster 2)

Source: Own conceptualization made with VOSviewer software.

The term **performance** in Cluster 2 signifies the effectiveness and efficiency of the processes, materials, or reactions studied, being loosely related to many of the other keywords:

- *catalysis*: the performance of catalysts and electrocatalysts represents a crucial current challenge, with research aimed at increasing reaction rates, lowering energy barriers and increasing selectivity in chemical reactions;
- *hydrogen production*: Performance measures of hydrogen evolution reaction (HER) efficiency in terms of production rates, overpotentials and material durability mark the evolution of hydrogen and hydrogen peroxide production. High-performance materials and systems are vital for cost-effective and scalable hydrogen production;

- *materials:* advanced materials such as nanoparticles or nickel-based electrocatalysts are often evaluated based on their performance in terms of stability, reactivity and adaptability in reaction environments;
- *Electrochemical performance and processes:* Performance in electrochemical setups, such as water splitting, is measured by the efficiency of electrodes and their ability to sustain reactions over time. The performance of catalysts in oxygen evolution reactions (OER) and reduction reactions is key to efficient energy conversion;
- *sustainability:* Performance in the context of green chemistry refers to reducing energy consumption, minimizing waste, and achieving high atom economy in synthesis. High-performance systems are essential for efficient carbon capture and conversion, such as converting CO2 into methanol or other valuable products;
- *Performance indicators:* stability, efficiency and kinetics are terms directly related to performance evaluation, where stability ensures long-term use, efficiency measures the use of energy or materials, and kinetics evaluates the reaction speed.

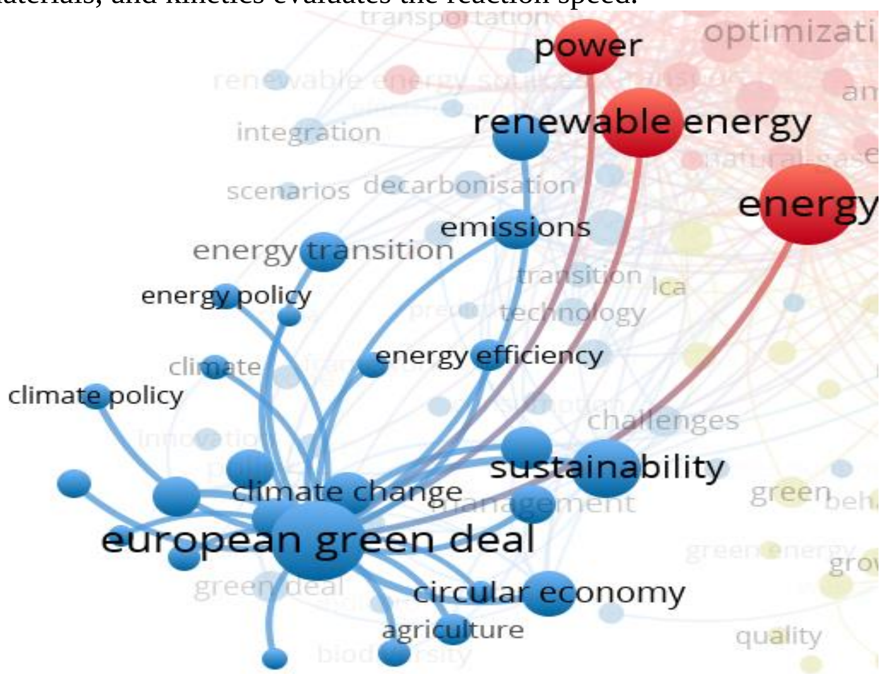

Figure 6. "European Green Deal" (Cluster 3)

Source: Own conceptualization made with VOSviewer software.

The term European Green Deal within cluster 3 acts as a central framework connecting many of the terms within it, as it represents a comprehensive strategy for sustainability, decarbonisation and economic transformation within the European Union. The Green Deal supports innovative solutions for carbon capture and storage to manage emissions from hard-to-reduce sectors, aligning with its objective of reducing net emissions by 2050. Here is how the European Green Deal influences various specific issues grouped in this cluster:

- *Energy and decarbonisation*: the European Green Deal prioritises energy efficiency and the transition to renewable energy to achieve climate neutrality. The policies under the Green Deal aim to reform energy systems, reduce dependence on fossil fuels and increase efficiency. Investments in emerging technologies such as hydrogen fuel and bioenergy are supported by the Green Deal to create a cleaner energy landscape and meet decarbonisation objectives;

- *Climate and environment*: in essence, the European Green Deal is a response to the climate crisis, integrating policies to reduce emissions, improve climate resilience and preserve biodiversity. Protecting ecosystems and halting biodiversity loss are explicit objectives under the Green Deal, with a focus on sustainable agriculture and habitat conservation;
- *Circular economy and practices*: The Green Deal strongly promotes a circular economy by encouraging the reuse, repair and recycling of resources, reducing waste and promoting sustainable economic models, such as the bioeconomy. The policies focus on sustainable consumption patterns to reduce the environmental footprint across the EU;
- *Policy and governance*: The European Green Deal is based on strong governance frameworks and measurable indicators to monitor progress in Member States. As an overarching EU framework, the Green Deal integrates regional policies to ensure a coordinated approach to sustainability;
- *Social and transition aspects*: Recognising that the ecological transition affects workers and communities differently, the Green Deal includes the "Just Transition Mechanism" to provide financial and political support to affected regions. The Green Deal directly addresses challenges such as balancing economic growth with sustainability and overcoming resistance to change;
- *Agriculture and land use*: The Green Deal reforms the common agricultural policy to support sustainable agriculture, reduce emissions and promote biodiversity-friendly practices;
- *Global and future perspectives*: The Green Deal not only shapes the EU's path on sustainability, but also serves as a model for global action, influencing trade policies and partnerships, including with important actors outside Europe.

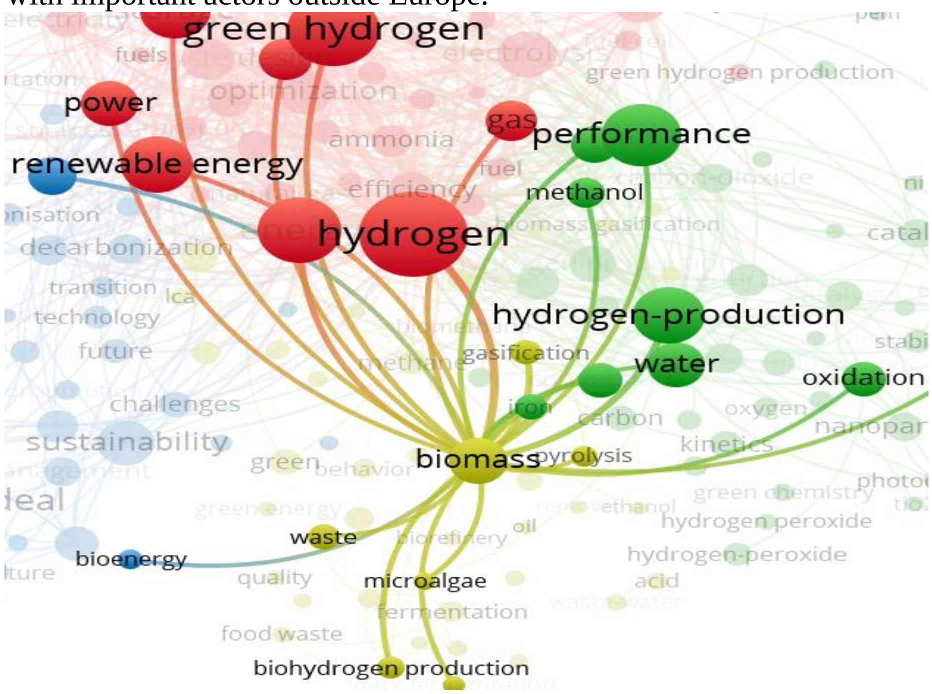

Figure 7. "Biomass" (Cluster 4)

Source: Own conceptualization made with VOSviewer software

The term **biomass** in Cluster 4 serves as a central element, connecting various technologies, processes and sustainability goals.

- *renewable energy*: Biomass serve as the primary feedstock for the production of biogas, biohydrogen and biomethane through processes such as anaerobic digestion and gasification.

Gasification of biomass produces synthesis gas, a mixture of hydrogen, carbon monoxide and methane, which serves as a precursor for renewable energy. These processes are crucial for creating alternatives to fossil fuels;

- *conversion technologies*: thermochemical processes of gasification and pyrolysis transform biomass into useful energy carriers, such as synthesis gas and bio -oil. They increase the utilization capacity of solid biomass. Anaerobic digestion is a biological process in which bacteria decompose organic biomass in the absence of oxygen to produce biogas. Dark fermentation is the specific process of producing biohydrogen from biomass under anaerobic conditions;
- *feedstock sources*: food waste which represents a sustainable resource for biogas and biohydrogen production, lignocellulosic biomass which includes plant-based materials (e.g., agricultural residues, forestry waste) which require pretreatment to increase conversion efficiency and microalgae which represents a type of biomass with high growth rates, used in biohydrogen and biofuel production due to its renewable nature;
- *environmental sustainability and optimization factors*: biomass is often considered carbon neutral, as the CO2 released during energy production is offset by the CO2 absorbed during the growth phase of the plants or algae. Biomass processes often integrate the reuse of waste materials, reducing the environmental impact. Temperature plays a critical role in biomass conversion technologies such as pyrolysis, gasification and anaerobic digestion, and for the realization of chemical processes we must ensure the quality of the biomass feedstock so that it does not contain contaminants that affect the efficiency of the process and the product yield;
- *industrial applications*: Biomass in biorefineries can be processed into multiple products, such as fuels, chemicals, and materials, similar to the role of crude oil in traditional refineries. Biomass-derived fuels (e.g., ethanol, methane) and chemicals contribute to green energy and sustainable industrial practices.

Conclusion

The study emphasizes the importance of green hydrogen as a central element of the transition to a sustainable and low-carbon economy. The bibliometric analysis conducted on the basis of scientific papers published in the period 2020-2024 offers the following perspectives and research directions:

- in the context of the global energy transition and the climate neutrality goals set by the European Green Deal, green hydrogen is acquiring a strategic role in the implementation of the European Green Deal and in achieving the decarbonization goals. The interest in this field is demonstrated by the significant increase in scientific research, especially in recent years.
- Water electrolysis using renewable sources remains the main method of obtaining green hydrogen;
- Green hydrogen used in transportation, industry and energy storage, has significant potential to reduce greenhouse gas emissions. Infrastructure development and reduction of production costs remain major challenges.
- European policies and funding initiatives through Horizon Europe or the Innovation Fund stimulate research and implementation of hydrogen technologies. Creating an ecosystem based on green hydrogen contributes both to energy security and to increasing economic competitiveness;
- a significant number of studies analyse the use of biomass and organic waste as alternative sources for hydrogen production, supporting the concept of circular economy and long-term sustainability.

Green hydrogen is a viable solution for the energy transition, and recent research confirms the importance of infrastructure development and supporting policies to accelerate the implementation of clean and sustainable energy sources. Green hydrogen technologies can be deployed more rapidly due to infrastructure development, supportive policies and cost reduction, the study highlights. The outlook for the coming years suggests an increase in investments in innovative technologies and a consolidation of the green hydrogen market in Europe and globally.

Given the strategic role of green hydrogen in energy transition and decarbonization, this study proposes the following courses of action for policymakers and industry:

- Supporting investments in green hydrogen infrastructure. Governments and industry stakeholders should collaborate to develop an integrated network for the production, transportation, and distribution of green hydrogen, including the use of regional hubs and dedicated transport corridors. Expanding European funding programs, such as Horizon Europe and the Innovation Fund, to support hydrogen infrastructure development is essential. At the member state level, there are already initiatives funded by European funds, demonstrating a growing interest in establishing hydrogen hubs.
- Reducing production costs both by supporting research and innovation and by fostering public-private partnerships.
- Adopting policies that stimulate demand and promote the use of green hydrogen in industry, transportation, and energy storage.
- Developing an attractive legislative framework for investors through tax incentives and regulations on green hydrogen certification, which can contribute to market development.
- Promoting the circular economy in hydrogen production by supporting research on using biomass and organic waste to produce hydrogen**,** thereby reducing dependence on scarce resources and ensuring long-term sustainability.

By implementing these measures, policymakers and industry can contribute to accelerating the transition to a low-carbon economy and strengthening green hydrogen's position as a viable solution for the future of energy.

Study limitations

The data under analysis in this study were extracted from the Web of Science platform, which was considered representative. Of course, different aspects could emerge from the analysis of other databases. In future research, the authors could expand the sample size and scope to make the results of the bibliometric analysis more comprehensive and meaningful to capture the eloquent aspects of green hydrogen.

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