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Advancing Sustainability: A Systematic Review and Bibliometric Analysis of the Hydrogen Economy in the Waste Sector

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ABSTRACT. The concept of the hydrogen economy has attracted significant attention in recent years due to its potential to revolutionize the way we manage waste and transition towards a more sustainable future. This paper aims to provide a comprehensive overview of the current state of research on the topic of the hydrogen economy, focusing on its application in the waste sector. The study utilizes systematic literature review and bibliometric analysis to identify key factors influencing the success rate of hydrogen economy implementation and to determine the definition of the hydrogen economy in the waste sector. The methodology used involved a combination of Systematic Literature Review (SLR) and Bibliometric Analysis (BA), which enabled detailed analysis of the results and provided a faster analysis of the practical literature than other methods of analysis. The findings of this study highlight the importance of understanding current research trends and gaps in the field, as well as the need for a deeper understanding of the factors that influence effective participation in the hydrogen economy. By reviewing the existing literature and identifying the most prominent research themes, this study aims to contribute to the development of a more comprehensive framework for the implementation of the hydrogen economy in the waste sector, ultimately supporting the transition towards a more sustainable and environmentally friendly model.

Keywords: hydrogen economy, waste management, sustainability, clean energy, bibliometric analysis

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1. INTRODUCTION

The threat of global climate change indicated by relentless greenhouse gas (GHG) emissions demands urgent action across all industrial sectors. One of several contributors is the waste industry, responsible for roughly 5% of global GHG outputs—primarily methane from decomposing organic matter in landfills [1]. It shows the importance of sustainable waste management solutions that mitigate emissions while generating energy. Hydrogen, as a versatile energy carrier, has emerged as a promising pathway to decarbonize the waste sector [2]. By converting waste into hydrogen through technologies like gasification and anaerobic digestion, this approach aligns with circular economy principles, reducing landfill reliance and fossil fuel dependence [3], [4].

Globally, hydrogen production from waste is gaining traction. Germany has demonstrated the feasibility of organic waste gasification for hydrogen generation, integrating it into regional energy systems [5]. Japan's regulatory frameworks, established in the early 2000s, have prioritized hydrogen as a strategic energy vector, including waste-derived sources [6]. Similarly, EU initiatives, such as the Fuel Cells and Hydrogen Joint Undertaking (2008–2020), have funded large-scale waste-to-hydrogen projects to advance energy conversion management [7]. These efforts highlight hydrogen's dual role in waste valorization and energy security, though scalability barriers persist, particularly in developing nations where financing gaps and technological readiness hinder adoption [8].

Sustainability assessments emphasize hydrogen's environmental benefits. Life cycle analyses reveal that waste-derived hydrogen can reduce GHG emissions by 50–80% compared to steam methane reforming, contingent on process efficiency [9]. However, optimizing energy inputs and minimizing carbon leakage remain critical challenges [10], [11]. A multi-stakeholder approach—encompassing policy incentives, infrastructure investment, and public engagement—is vital to overcoming these barriers. For instance, Sweden's collaborative model between

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municipalities and energy firms has accelerated biogas-to-hydrogen projects, demonstrating the importance of institutional synergy [12].

Economically, hydrogen production costs from waste remain higher than conventional methods, but declining electrolyzer prices and scaling effects are improving viability [13]. Feasibility studies suggest that integrating carbon pricing mechanisms could further enhance competitiveness [14]. Nevertheless, technology transfer and capacity-building programs are essential to enable global uptake, particularly in regions lacking R&D infrastructure [15], [16].

Despite growing research, a systematic synthesis of knowledge gaps, trends, and definitions in waste-based hydrogen systems is lacking. This study employs a Systematic Literature Network Analysis (SLNA)—integrating Systematic Literature Review and Bibliometric Analysis—to: (1) map the evolution of hydrogen economy research in the waste sector, (2) identify key technical, economic, and social determinants of success, and (3) delineate the hydrogen economy's conceptual boundaries within waste management. The findings aim to inform policymakers, researchers, and industry stakeholders in advancing sustainable energy transitions. Aims of the study are systematically maps the hydrogen economy's role in waste management through SLNA, identifying critical success factors and conceptual frameworks to guide sustainable policy and innovation strategies.

2. MATERIALS AND METHODS

2.1 Conceptual Framework of the Methodologies

This study was conducted using a combination of Systematic Literature Review (SLR) and Bibliometric Analysis (BA), called the Systematic Literature Network Analysis (SLNA) approach, this method was used to measure recent developments and research gaps in hydrogen economy studies to develop a deeper understanding of the factors that influence effective participation in hydrogen economy. The methodology used follows the same guidelines as the articles published by [17], [18]. BA is commonly used to cover reviews of published papers and look for patterns of the current state of research by retrieving and analyzing datasets of citations, keywords, and titles along with abstracts. As a methodological approach for relationship analysis, BA offers advantages in terms of efficiency, practicality, and its ability to provide extensive insights for identifying research gaps[19].

The BA method has the disadvantage that little in-depth analysis is provided. To overcome this, SLR is used to provide a detailed analysis of the results obtained and provide a practical literature analysis that is faster than other analysis methods [20].

There are several phases in the development of the methodology. The first phase was to determine the scope of the literature analysis by framing several research questions as a framework for the literature analysis process. The research questions used were as follows.

RQ1 What is the current state of research, gaps, and potential future research on the topic of hydrogen economy?
RQ2 What is the definition of hydrogen economy in the waste sector?
RQ3 What are the main factors that influence the success rate of hydrogen economy implementation?

The second phase was to find and define a strategy to define the appropriate metadata of the scientific database. This phase follows the guidelines for the PRISMA 2020 methodology [21]. Study selection, evaluation, identification and inclusion criteria are further described in the "Data Collection" section. The Scopus database used to generate the metadata was retrieved on April 5, 2024.

2.2 Data Collection

The steps of the data collection procedure are briefly described, as they can be used to replicate the methodology in the future. First, several keywords were entered into the Scopus database. Keyword selection is an important parameter in SLR studies as it can affect the results and interpretation of the overall review [17]. The keywords entered into the database were "hydrogen", AND "economy", AND "policy", AND "future". In this step, 1,045 documents were identified. Subsequently, consecutive keyword exclusion criteria were applied using an automated filtering process, including year of publication, document type, language used, and source type. The publication year was limited to 2015-2023 (763 documents), and the document type searched was conference articles and papers (150 documents). The language type used was English (150 documents) and the articles used were limited to journals and conference proceedings (143 documents). At the end of the keyword restriction process, 143 documents that had a correlation to the main keyword were found. Manual checking was done by separating documents based on title and abstract suitability. At the end of the checking, 117 documents were included in the bibliometric analysis. As for the content analysis used to answer RQ2 and RQ3, all documents found after including all keywords were analyzed in depth, with additional references added in the review.

2.3 Data Analysis

This study was conducted using several software, namely VOSviewer and Orange Data Mining 3.34 to develop bibliometric networks, mapping, and analysis. First, VOSviewer was used to develop common authorship (author and country), common context (keywords and terms generated through title and abstract analysis), and citation network analysis (of the documents used). Keywords, titles, and abstracts were also analyzed using text mining available in Orange Data Mining 3.34 software [18]. In this model, the results from VOSviewer and Orange Data Mining 3.34 software will be compared and integrated to get a clear and structured picture of the current research topic, which is interesting, new, and still debated. Before the core analysis is performed, some pre-processing criteria for VOS mapping, word storage with clouds, and topic modeling are used during network map generation.

VOS Techniques

Current research trends and status were visualized and descriptively explained using the collected metadata. Subsequently, several analyses, such as co-authorship networks from authors and countries, citation networks, co-occurrence keywords, titles, and abstracts were conducted, with inclusion and preprocessing criteria as shown in table 1. The VOS technique is also claimed to provide a better visualization of a set of metadata compared to other distance-based maps, such as VxOrd, Kopcsa–Schiebel, and multidimensional scaling (MDS). VOSviewer uses the visualization of similarities (VOS) technique, which can display a set of keywords or nodes between certain distances based on their strength. The smaller the distance, the stronger the relationship between the two keywords or nodes. As a result, keywords or nodes do not overlap in the VOS cluster map. The link shown in the VOS maps represents the relationship between the nodes or keywords. Every link possesses strength, where a higher value indicates a stronger connection. For instance, a link strength can represent shared references between two articles, joint publications of two researchers, or the frequency of the two terms appearing together in publications. A higher-value link and thicker nodes indicate a robust relationship between the two related nodes. Moreover, the detail of statistical approaches for generating the VOS maps was published elsewhere [22].

In this study, citation and co-authorship networks (authors and countries) were analyzed. However, only the co-authorship country map is shown in the manuscript, whereas the co-citation and co-authorship results are presented in a table showing the most cited papers and most productive authors in the field (see Supplementary Materials for access to the generated table). Co-authorship analyses were used to visualize the partnership or cooperation patterns among authors, organizations, and countries on the topic of hydrogen economy. As such, understanding scientific collaboration is essential for fostering innovation in the hydrogen economy, as it facilitates access to diverse expertise and interdisciplinary knowledge [23]. As mentioned previously, this study examined which articles were most cited in the field of hydrogen economy studies. The goal was to determine the extent to which various journals or articles have discussed this topic. The co-occurrence of keywords and terms from the titles and abstracts was also developed to understand the gaps and recent trends in hydrogen economy-related research. Co-occurrence of keywords stands only for the author keywords presented in each article's metadata. The co-occurrence of terms represents words from the title and abstract of the collected metadata. VOSviewer classifies keywords or terms into several clusters that have close relationships and similarities. Larger nodes reflect the most popular keywords or terms in publications related to the research topic [24].

Word Clouds and Topic Modelling

Several analyses, such as word clouds, topic modeling, and multidimensional scaling (MDS), were used together with VOSviewer to visualize the corpus (Fig. 1). Corresponding to the word cloud, the size of a word is defined as the frequency of words in the corpus. The central word in the cloud is the most used for the specified topic, whereas the smaller and farther from the center are used less often. Furthermore, Latent Dirichlet Allocation (LDA) was used to generate hidden topics in the titles, abstracts, and keywords of hydrogen economy studies.

Table 1 Inclusion and Pre-processing Criteria for Bibliometric Analysis

Analysis	Pre-processing Criteria
Co-authorship authors	In full counting, the minimum number of documents of an author is set to 3, the minimum number of citations of an author is set to 10, and the map shows all set of networks
Co-authorship countries	In full counting, the minimum numbers of documents of a country is set to 5, the minimum number of citations of a country is set to 10
Citation network	In full counting, the minimum numbers of citations of a document is set to 4, and the map shows only the most extensive set of networks
Co-occurrence author keywords	In full counting, the minimum numbers of occurrences of a keyword is set to 6, and the map shows only the most extensive set of networks
Co-occurrence terms	In full counting, the minimum number of term occurrences is set to 11.
Word clouds	Hydrogen economy, policy, future
Topic modeling	HTML
Multidimensional scaling	Tokenization: regexp, pattern \w+
Marginal topic probability	Filtering: stopwords (English); numbers; document frequency 0.10–0.90; regexp; LDA is set to 7 for title and abstract, and 4 for author keywords

LDA is a classic natural language processing (NLP) method that can be applied in bibliometric analysis using topic modeling to generate several specific topics in a corpus using machine learning (ML). It makes a list of key terms based on how often words are used together and clusters them into topics based on how often these key terms appear in each article [25]. Unlike the VOS clustering technique, LDA produces several keywords that may overlap among topics. In addition, LDA was employed to find hidden or missing topics that could not be extracted using the VOS technique. Topic modeling was then validated using Multidimensional Scaling (MDS) and Marginal Topic Probability (MTP). MDS analysis was used to detect similarities between the topics; the closer the distance between topics, the more similar the topics, and vice versa. The MDS can simplify complex data while maintaining its main message). An MTP bar plot was constructed to visualize the topics in the corpus text, highlighting the strongest and weakest ones, based on the output of the LDA model [26].

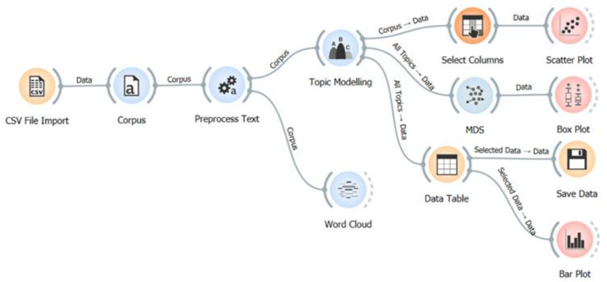


Fig. 1. Word Clouds and Topic Modeling Framework Using Orange Data Mining 3.34.

Qualitative Content Analysis

The methodology for qualitative content analysis followed [27], in which the analysis was used to analyze and explain the definitions of hydrogen economy, Net Zero Emission (NZE), and transition of NZE in the waste sector. Mixed protocols (inductive and deductive) were used to define, review, and synthesize the concept using the available literature. This hybrid review is powerful enough to explain the research trends and status, definition, and extract several pieces of information from the literature, thus filling research gaps [28].

3. RESULT AND DISCUSSION

3.1 Bibliometric Analysis Results

This subsection focuses on the results of the bibliometric analysis, which include the identification, screening, and inclusion phases. The analysis focuses on the results of VOS techniques, word clouds, and topic modeling.

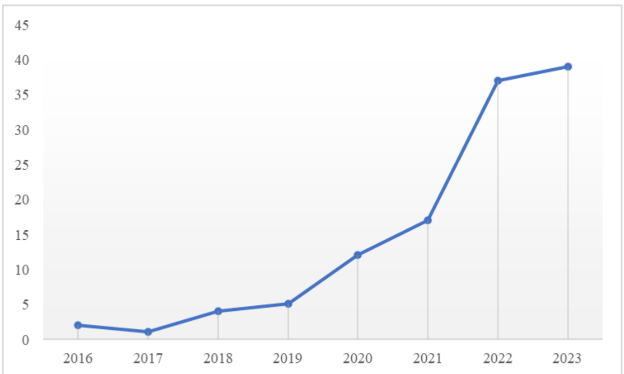


Fig. 2. Scientific Production of Hydrogen Economy-Related Papers

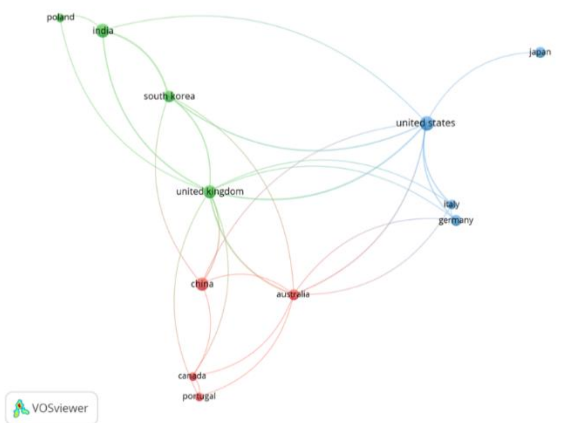
Current Research Trends and Status

The analysis begins by identifying research trends by publishing documents in the collected metadata. Research trends can be evaluated by understanding the evolution and trends of scientific production. As shown in Fig. 2, the number of publications on hydrogen economy research decreased in 2017 and after that there was an increase in each year until 2023, the most drastic increase occurred in 2022. Despite the pandemic, the amount of research on the hydrogen economy is not affected and has even increased. The increasing trend in hydrogen-related publications reflects a broader shift toward sustainable resource utilization, in which waste streams are increasingly viewed as valuable inputs rather than residual by-products [29]. This trend also indicates growing global attention toward low-carbon energy systems capable of integrating waste-derived resources into energy production pathways. The transition toward hydrogen-based systems highlights the strategic role of waste valorization in supporting energy security and climate mitigation objectives [30].

Table 2 Previous Studies Related to Participatory Hydrogen Economy and Its Factors

Dimension/ Factors	Terms or Keywords	References
Socioeconomic	Affordability	[31], [32], [33], [34], [35]
	Economy	[36], [37], [38], [39], [40], [41]
	Environmental ethics	[42], [43], [44], [45]
Institutional	Policy and Regulations	[46], [47], [48], [49]
	Organization and collaboration with multiple stakeholder	[50], [51], [52]
	Environmental governance	[53], [54]

(a)



(b)

Fig. 3. Co-authorship Networks Based on Country Affiliations: Overlay Visualization (a) and Network Visualization (b)

The scientific literature on the hydrogen economy can also be analyzed based on the journals that publish the research, the country of affiliation of the researcher (Fig. 3), the researchers who contributed to the research (Table 2), and the papers that have the highest citations in the study area (Table 3). Table 2 presents the key factors influencing the participatory hydrogen economy, derived from a comprehensive bibliometric analysis of peer-reviewed articles retrieved from the Scopus database using keywords such as hydrogen economy, energy transition, policy, sustainability, and renewable energy. Bibliometric mapping of titles, abstracts, and author keywords revealed recurring terms and co-occurrence patterns that form distinct thematic clusters. Terms such as cost, affordability, investment, and economic feasibility were grouped under the socioeconomic dimension, while sustainability, carbon emissions, environmental impact, and ethics constituted the environmental ethics dimension.

These dimensions are closely linked to waste management practices. The socioeconomic dimension highlights the potential of converting municipal solid waste, wastewater sludge, and industrial by-products into hydrogen as a means of reducing disposal costs while generating economic value [55]. Meanwhile, the environmental ethics dimension reflects the role of waste-to-energy systems in reducing landfill dependency, mitigating greenhouse gas emissions, and supporting sustainable resource use [56]. Furthermore, the identification of policy, regulation, and governance factors emphasizes the importance of integrated institutional frameworks that align energy planning with waste management systems. Such coordination is essential to integrate waste management with hydrogen production strategies [57].

Based on the country affiliation of contributors, the United States had the highest affiliation, followed by China, the United Kingdom, India, Italy, Poland, South Korea, Australia, Canada, Portugal, Germany and Japan. The most recent publications regarding hydrogen economic studies come from Italy, Poland, India, and Canada, while China, Germany, and Japan are the oldest. Based on Fig. 3(b), several clusters can be formed, indicating the collaborating countries and similar themes of their papers. For example, researchers from the United States, Japan, Italy, and Germany are colored blue, indicating the same or similar research focus on the hydrogen economy.

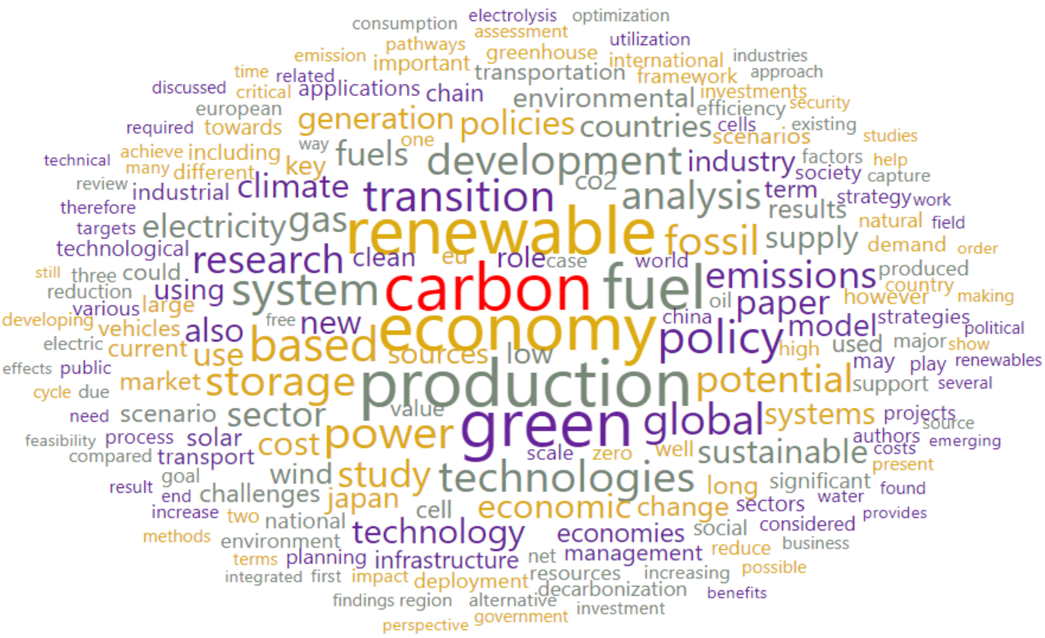
VOS Mapping of Title, Abstract, and Keywords

According to the authors' keywords, several prominent clusters emerge from the VOS mapping analysis. The most recent keywords include natural gas, energy transition, power, green hydrogen, cost, commerce, environmental impact, sustainability, and alternative energy. These terms reflect a growing research focus on transitioning toward low-carbon and resource-efficient energy systems. Importantly, this transition is closely linked to waste management strategies, particularly through the utilization of waste-derived resources. The emergence of keywords such as sustainability, environmental impact, and green hydrogen suggests increasing scholarly attention to circular economy principles, where waste is no longer viewed solely as a disposal problem but as a potential energy input. In contrast, earlier keywords, such as decarbonization, carbon dioxide, carbon capture, energy efficiency, and fuel cells, reflect an earlier research phase focused primarily on emission reduction and energy system optimization. The shift from emission control toward integrated energy–waste solutions indicates an evolution in research orientation, aligning hydrogen development with broader waste management and resource recovery strategies.

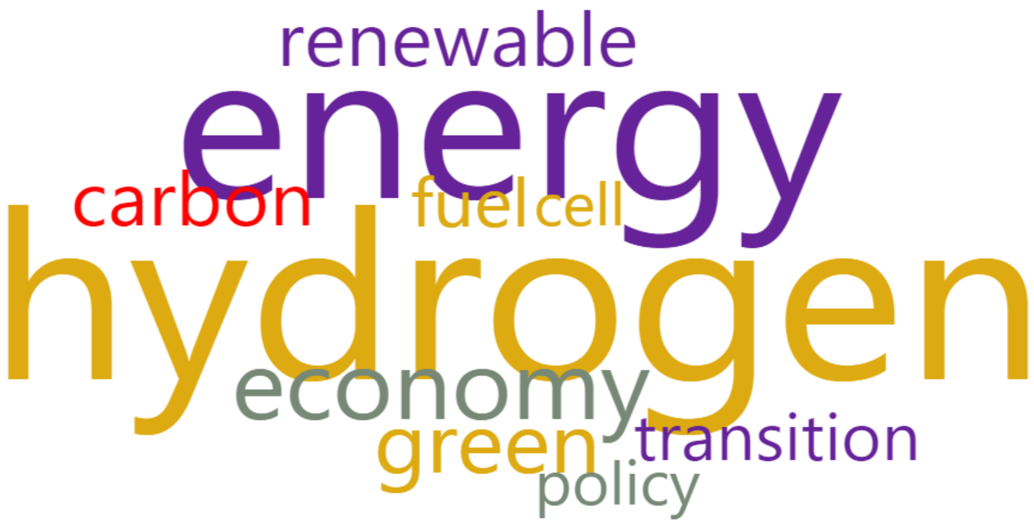
Table 3 List of Topics Generated by Terms in Title and Abstract and Author Keywords

Topic Label	Terms in Title and Abstract	Topic Label	Author Keywords
Topic 1 Carbon Management and Global Energy Economy	Carbon, economy, storage, fuel, global, research, management, transportation, low, fossil	Topic 1 Hydrogen economy transition	Hydrogen, energy, economy, renewable, green, transition, policy, fuel, carbon, cell
Topic 2 Green Economy and Sustainable Fuel Production	Green, economy, production, fuel, sustainable, economic, development, based, study, process	Topic 2 Fuel cells and hydrogen integration	Fuel, cell, hydrogen, economy, carbon, transition, energy, green, renewable, policy
Topic 3 Policy and Economic Analysis of Hydrogen in Japan	Economy, japan, fuel, policy, analysis, power, system, production, green, model	Topic 3 Renewable energy and hydrogen policies	Energy, renewable, green, hydrogen, policy, economy, carbon, fuel, transition
Topic 4 Renewable Fuels and Economic Transition	Renewable, production, fossil, economy, fuel, potential, fuels, policy, supply, transition	Topic 4 Carbon management in hydrogen economy	Carbon, energy, hydrogen, fuel, renewable, transition, economy, green, policy, cell
Topic 5 Carbon and Climate Impact on Global Economy	Carbon, economy, green, global, storage, climate, emissions,	Topic 5 Green energy transition	Carbon, hydrogen, economy, transition,

Topic Label	Terms in Title and Abstract	Topic Label	Author Keywords
	transition, production, gas		green energy, policy, renewable, fuel, cell
Topic 6 Technological Systems and Renewable Energy Development in the EU	System, technologies, power, production, research, EU, green, renewable, development, analysis	Topic 6 Policy and energy in hydrogen economy	Energy, policy, green, hydrogen, transition, renewable, fuel, cell, economy, carbon



(a)



(b)

Fig. 5. Word Clouds of (a) Terms in Title and Abstract and (b) Author Keywords

Word Clouds

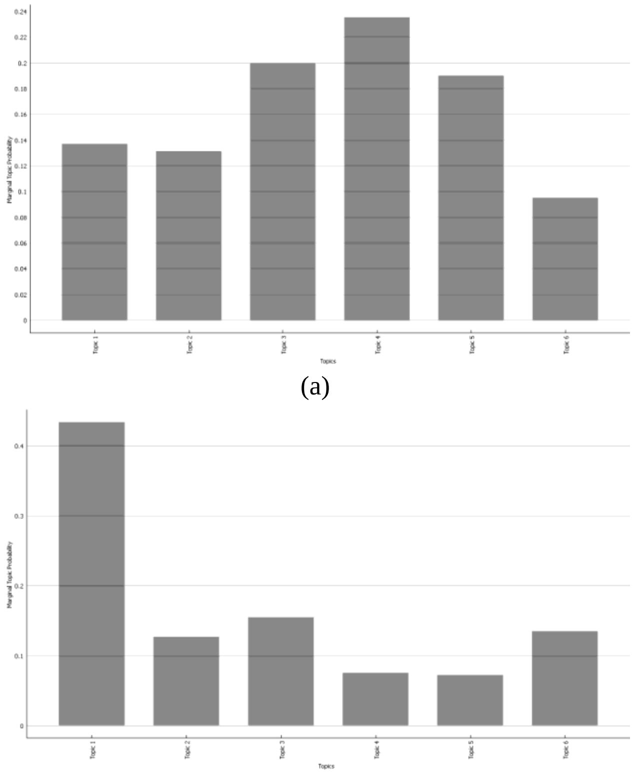
The word clouds of the terms and keywords are shown in Fig. 5. Word clouds are used to represent the occurrence frequency of keywords and terms in the title abstract by their density in the publications [58]. As shown in Fig. 5(a), the highest frequencies of terms found in the title and abstract (excluding the word 'hydrogen--economy') were carbon (f = 204), production (f = 159), renewable (f = 155), green (f = 149), and fuel (f = 136). In Fig. 5(b), the most frequent terms found in the authors' keywords are hydrogen (f = 120), energy (f = 101), economy (f = 35), and green (f = 27). The high frequency of carbon, production, renewable, green, and fuel suggests that these are the central themes or topics in metadata. This may also suggest that the primary focus of hydrogen economy is on carbon production and renewable energy. The words carbon and fuel may indicate a strong focus on the energy dimension, which is possibly looking at how carbon production and renewable energy factors play an important role in hydrogen economy.

These findings align with waste management objectives, particularly the reduction of landfill disposal and greenhouse gas emissions through waste-to-energy technologies. Similarly, the dominant keywords in author-defined terms, such as hydrogen, energy, economy, and green, highlight the strategic role of hydrogen as a bridge between energy transition and waste valorization. The frequent appearance of these terms indicates that waste streams are increasingly considered as feedstocks for clean energy production, reinforcing the role of hydrogen as a key enabler of circular economy practices [59].

Topic Modeling of Title, Abstract, and Keywords

LDA topic modeling identifies several latent or hidden topics in a given corpus [60]. As LDA generates similar words that may overlap in each topic, the first occurrence becomes the keyword for labeling the topics in this study. From Table 2, it can be concluded that several "hidden" topics can be generated through LDA modeling. For instance, several topics, such as carbon management and global energy economy (topic 1), green economy and sustainable fuel production (topic 2), policy and economic analysis of hydrogen in Japan (topic 3), renewable fuels and economic transition (topic 4), carbon and climate impact on global economy (topic 5), technological systems and renewable energy development in the EU (topic 6), were not found in the VOS map. Topic modeling usually uses marginal probability to rank the best candidate topic in a corpus [61].

The most significant MTP result in the title and abstract is found in topics 2 and 4, as can be seen in Fig. 6, which is related to hydrogen economy and renewable energy. Meanwhile, topic 3 (renewable energy and hydrogen policies) has the highest MTP in the author keywords. This is also in line with the MDS results that show topic 2 and 4 in the title and abstract have the strongest link, which are closely similar. The third most prominent topic in the title and abstract is topic 1, which is interpreted as a factor affecting hydrogen economy. Interestingly, the impact of climate change on the watershed showed different patterns between the VOS mapping and MTP results. In VOS mapping, a giant cluster was found in the hydrogen economy to energy policy, while in LDA modeling, the topic related energy policy resulted in a smaller value of MTP. Because the impact of green policy on hydrogen economy management is also the newest topic in this field, this topic is considered a gap that can be discussed further in scientific literature. Based on these findings, several Hydrogen Economy-related topics are gaining interest, including (1) definition of hydrogen economy, (2) hydrogen policy, (3) prospect of hydrogen economy, and (4) challenge of hydrogen economy. In the following subchapter, the fourth topic is discussed in depth using a narrative discussion.



(a)

(b)

Fig. 6. Marginal Topic Probability (MTP) of Terms in Title and Abstract (a) Author and Keywords (b).

3.2 Definition of Hydrogen Economy

Hydrogen economy is a concept that utilize hydrogen as a primary energy carrier, replacing fossil fuels in various sectors such as transportation, power generation, and industrial processes. This vision involves the production, storage, transportation, and use of hydrogen as a clean and efficient energy source. The idea is to create a closed-loop system where hydrogen is generated from renewable energy sources, used as a fuel, and then converted back into water and heat, thereby minimizing waste and environmental impact [62].

The hydrogen economy is envisioned as a future energy system where hydrogen plays a central role as a carbon-free energy carrier, aiming to reduce greenhouse gas emissions and mitigate climate change. The need for a hydrogen economy arises from several key factors, such as reducing emissions, energy security, environmental benefits, and economic benefits. Hydrogen can be produced from renewable energy sources, making it a cleaner alternative to fossil fuels. Hydrogen can be used as a flexible energy carrier, enabling the efficient storage and transport of energy. This flexibility is crucial for ensuring energy security and reliability in the face of intermittent renewable energy sources. Therefore, hydrogen can help reduce greenhouse gas emissions and air pollution, contributing to a cleaner and healthier environment. This is particularly important for urban areas where air quality is a significant concern. Besides that, hydrogen economy has the potential to create new industries and jobs, driving economic growth and development. It also offers opportunities for cost savings and increased energy efficiency in various sectors [63].

3.3 Hydrogen Policy

Hydrogen policy refers to the comprehensive approach and strategies developed by governments and international organizations to support the development and deployment of green hydrogen, which is produced from renewable energy sources. This policy aims to reduce greenhouse gas emissions and mitigate climate change by promoting the use of hydrogen as a clean energy carrier in various sectors such as transportation, power generation, and industry [64]. Hydrogen policy is needed for several reasons, such as climate neutrality, energy security, environmental benefits, and future energy systems. Hydrogen is a key component in achieving climate neutrality by 2050. It can be produced from renewable energy sources, making it a zero-emission energy carrier. This is crucial for reducing greenhouse gas emissions and mitigating climate change. Hydrogen can improve energy security by reducing dependence on foreign oil and increasing the use of domestic renewable energy sources. This enhances energy independence and reduces the impact of price fluctuations. Hydrogen can help reduce air pollution and greenhouse gas emissions, contributing to a cleaner and healthier environment. It is particularly important for urban areas where air quality is a significant concern. Hydrogen is envisioned as a key component in the future energy system, enabling the transition to a low-carbon economy. It can be used as a clean energy carrier in various sectors, including transportation, power generation, and industry [65].

3.4 Prospect of Hydrogen Economy

The hydrogen economy is envisioned as a future energy system where hydrogen plays a central role as a clean energy carrier, aiming to reduce greenhouse gas emissions and mitigate climate change. Hydrogen can be produced from renewable energy sources and used as a fuel in various sectors such as transportation, power generation, and industry.

The prospects of hydrogen as a sustainable fuel have gained significant attention as countries aim to achieve net zero emissions by 2050. Hydrogen is seen as a promising solution for decarbonizing sectors that are difficult to transition to cleaner energy sources, including heavy industry, transportation, and heating. In order to achieve net zero emissions by 2050, a comprehensive suite of technologies will be necessary to transform the energy infrastructure. This transformation will involve a combination of energy efficiency measures, behavioral changes, advancements in electricity generation, the adoption of renewable energy sources, the use of hydrogen and hydrogen-based fuels, and the implementation of Carbon Capture, Utilization, and Storage (CCUS) technologies. To achieve this, hydrogen production needs to become significantly more efficient and transition to zero or low-carbon emitting methods [66].

Hydrogen is a vital component for the decarbonization in the industry. However, the techonogies required to process hydrogen-based fuels still needs further advancements before it can significantly contributes to decarbonization. In 2021, the world's first pilot project for carbon-free steel production using low-carbon hydrogen began operation in Sweden. Additionally, a new initiative for ammonia production in Spain started in late 2021, utilizing variable hydrogen derived from renewable sources. For the next several years, numerous projects are expected to come online with significant capacities. Hydrogen projects for commercial applications such as cement, glass, and ceramics production are also planned [67].

The majority of government policies focus on reducing CO2 emissions from hydrogen production, with less emphasis on strategies to boost demand. While countries like Japan, Korea, France, and the Netherlands have set targets for fuel cell electric vehicles (FCEVs), a significant shift in demand generation is needed to increase the contribution of low-carbon hydrogen to clean energy transitions. Governments are starting to announce a range of policy measures, including auctions, carbon prices, mandates, quotas, and public procurement requirements, but these initiatives have not yet proven effective. If implemented quickly and widely enough, these measures could lead to more initiatives to increase hydrogen demand [67].

Through advancements in technology and expanded implementation, there is a significant opportunity to reduce hydrogen production costs. This is illustrated by the IEA's Net Zero Emissions by 2050 Scenario, which projects that the cost of hydrogen produced from renewable sources could reach $1.30 per kilogram by 2030 in areas with abundant resources, making it competitive with hydrogen produced from natural gas using carbon capture, utilization, and storage (CCUS). In the long term, solar photovoltaic (PV) becomes less expensive, and hydrogen produced from renewable electricity could fall below $1.00 per kilogram in some locations, with a range of $1.00 to $3.00 per kilogram in the Net Zero Emissions Scenario [68].

3.5 Key Principles and characteristics of Hydrogen Economy

Several characteristics of the Hydrogen Economy can be identified from a published literature review. As shown in Fig. 5, the first is urgency to shifting toward renewable energy resources. As the word of Hydrogen Economy are linked to “renewable energy” and “storage of energy”, the systems developed in Hydrogen Economy is used to decarbonize sectors that are difficult to electrify, such as heavy industry, transportation, and heating, by providing a clean alternative to fossil fuels [69], [70].

As transportation and storage of energy, hydrogen is used to transport and store energy in the form of liquid or gaseous hydrogen, which can be easily produced and used as a fuel. Local production and consumption should be prioritized to suppress the energy required for transportation and storage, making it more viable option for energy transition.

3.6 Real World Examples of Hydrogen Economy Implementation

Some good stories of Hydrogen Economy implementation were taken from the published literature. For instance, the hydrogen were fused with the existing natural gas infrastructure to optimize the Hungarian Energy Transition. This analysis utilizes a European energy supply model with strong interactions between the conversion sector and the hydrogen system to examine the requirements for geological hydrogen storage and their utilization over the course of a year. The study focuses on the distribution of electrolyzers across Germany and the role of hydrogen transport networks in aligning supply and demand [71].

Regarding the development of a hydrogen transport infrastructure, two key findings emerged. One, domestic German network connecting electrolytic hydrogen production sites in northern Germany to hydrogen demand hubs in western and southern Germany is economically efficient. This domestic network would facilitate the transportation of hydrogen from production sites to areas of high demand, ensuring a reliable supply chain. Two, the European interconnection which connecting Germany to a European hydrogen transport network with interconnection capacities between 18 GWH2 and 58 GWH2 is cost-efficient to meet Germany's substantial hydrogen demand. This interconnection would enable Germany to access a broader hydrogen supply and reduce reliance on domestic production, ensuring a stable and efficient hydrogen supply chain across the continent [71].

In Republic of Korea, the scope of hydrogen energy is being expanded as a key driver of national economic growth and industrial competitiveness, particularly to address environmental concerns like climate change. The impact of this expansion on the energy system and national greenhouse gas (GHG) emissions will significantly depend on the specific hydrogen energy supply chain scenario implemented [37].

The energy and environmental impacts of various hydrogen energy supply chain scenarios on the national energy system were analyzed using the TIMES model, based on three key perspectives. One, technology development is varied in terms of the level of development of key technologies, such as electrolysis, fuel cells, and hydrogen storage. Two, Renewable Energy Contribution differs in the proportion of renewable energy sources contributing to the power generation sector, which directly affects the overall energy mix and environmental performance. Three, Hydrogen Production Method Portfolio were defined by the relative importance of different hydrogen production methods, including electrolysis, steam methane reforming, and other methods. From the perspective of the national energy system of the Republic of Korea, transitions toward renewable energy, particularly solar and wind power, along with advancements in water electrolysis technologies, play a critical role in reducing GHG emissions and supporting a more sustainable energy future [37], [46].

3.7 Factors Affecting Successful Hydrogen Economy

Participation from strong stakeholders and society is an essential and fundamental approach to implement the Hydrogen Economy and reduce the GHG emissions [37], [72]. Several key factors influence the successful implementation of a Hydrogen Economy, as summarized in Table 3. The terms/keywords were extracted from literature searching and determined based on their relationship as Hydrogen Economy factors.

Socioeconomic

Socioeconomic factors are the most influential contributing factors to implementation of the Hydrogen Economy. Several subfactors can be identified, including affordability, economy, and environmental ethics.

1. Affordability
   Despite efforts to advance the field, progress in hydrogen production remains slow due to the high cost of production. To facilitate understanding, different color categories are used to distinguish between various hydrogen production methods based on their primary energy sources, making it easier to identify and compare different approaches. Yet based on the future trend, green hydrogen is expected to dominate future production due to its cost competitiveness over blue hydrogen and cheaper renewable electricity [73].
2. Economy
   The future perspectives of the Hydrogen Economy also based on the region and country current economic situations. The more stable the economic situation and the supply chain, the easier to shift into hydrogen economy in the future. The energy and environmental effects of hydrogen energy supply chain were analyzed quantitatively from different perspectives and it can show the highest demand of electricity and the transition of the power sector to renewable energy to reduce the GHG emissions [37].
3. Environmental ethics
   Environmental ethics are essential to implement the hydrogen economy, especially the awareness of strong stakeholder and society. Participatory community and strong stakeholders must be enhanced and developed by building a knowledge-based awareness and internalizing the capacity of each society member to understand the future choices of renewable energy. Since society is still less interested in the hydrogen economy and strong stakeholder are still searching for less cost renewable energy, enormous efforts are needed to enhance their awareness and acceptance of the technologies shifting [74].

Institutional

Previous studies have revealed that institutional effectiveness is a crucial factor in guaranteeing people's involvement in environmental governance, including hydrogen economy. The institutional factors for establishing ideal participatory hydrogen economy include several forms: regulations [46], [47], [48], [49], organization and collaboration with multiple stakeholder [50], [51], [52], and environmental governance related to hydrogen economy [53], [54].

1. Policy and Regulation
   Regulations related to hydrogen economy involve city, provincial, and central governments as policymakers.

The rule becomes benchmark in integrating the roles of government and community so that they are mor optimal in managing the socioeconomic environment. Despite regional plans to transition to a hydrogen economy, many policymakers and experts remain concerned about the institutional and technological challenges that need to be addressed. Specifically, the lack of a comprehensive hydrogen infrastructure, including refueling stations and transportation networks, hinders the widespread adoption of hydrogen as a fuel. Additionally, the high cost of production and the limited availability of green hydrogen further complicate the transition.

2. Organization and collaboration with multiple stakeholders
   Hydrogen economy implementation requires the synergize between government, society, and multiple stakeholders because hydrogen economy requires collaboration to form integrated and sustainable policies to shift from non-renewable energy resources to renewable energy resources for all aspects in the region including the supply chain. Thus, collaboration among stakeholders is essential to coordinate research efforts and develop practical, implementable strategies for hydrogen economy deployment [66]. To establish an integrated, participatory, and sustainable hydrogen economy, institutional strengthening and clear regulatory frameworks are necessary to ensure equitable roles among all actors [75].
3. Environmental ethics
   It is necessary to increase the capacity of private organizations and NGOs that have the potential to participate actively in hydrogen economy research and implementation. The lack of government attention to supporting hydrogen economy, overlapping roles of central and local governments, and unclear hydrogen economy policies can lead to sectoral conflicts between the central and local governments. These conflicts can occur because central and local governments have different perspectives, so there is struggle and handover of responsibilities for hydrogen economy [42].

3.8 Challenges and Strategies

The implementation of hydrogen economy can face several challenges, such as lacks coordinated policies for hydrogen economy towards natural gas, infrastructures and technology issues, capital working issues, and long-term sustainability considerations. As an example of coordinated policies for a hydrogen economy, a shift towards a hydrogen-based economy would significantly impact the petroleum refining sector and the output mix of petroleum products. In this scenario, the reduced demand for gasoline would not only affect the demand for oil but also alter the refinery's economics. Gasoline, which is currently a premium fuel, would become a joint product alongside other petroleum products [36], [76]. Regarding infrastructure and technology, the transition requires a high degree of adaptability in both systems and facilities to accommodate hydrogen applications. These challenges are closely linked to capital investment constraints, as hydrogen infrastructure development demands substantial financial resources. Moreover, hydrogen research and implementation programs that rely heavily on external funding may face sustainability risks once financial support declines due to limited awareness and commitment. Hence, the successful implementation of a hydrogen economy requires coordinated development across all sectors to ensure long-term viability and resilience.

4. CONCLUSION

Based on the bibliometric analysis, several conclusions can be drawn. Research on hydrogen economy has seen significant growth in recent years since 2017, where the most drastic increase occurred in 2022. Despite the pandemic, the amount of research on the hydrogen economy is not affected and has even increased. Based on the country affiliation of contributors, the United States had the highest affiliation, followed by China, the United Kingdom, India, Italy, Poland, South Korea, Australia, Canada, Portugal, Germany and Japan. The most recent publications regarding hydrogen economic studies come from Italy, Poland, India, and Canada, while China, Germany, and Japan are the oldest. The analysis showed that several clusters can be formed, indicating the collaborating countries and similar themes of their papers. For example, researchers from the United States, Japan, Italy, and Germany are colored blue, indicating the same or similar research focus on the hydrogen economy. The bibliometric analysis of this study was limited to the keywords inputted in the Scopus database, which may result in bias and not reflect all publications on this topic. Even though this limitation has already been established by conducting a rigorous review in the subsequent sub-chapter using narrative review, the bibliometric analysis may not reveal all hidden gaps related to the publication of hydrogen economy study. Future research should incorporate broader keyword variations to better capture the full scope of hydrogen economy studies.

Hydrogen economy has been one of the efforts carried out and developed for renewable energy resources adaption over the last few years. Hydrogen economy is essential to reduce the GHG produced by a country or region, thereby the future research and implementable practical hydrogen economy towards supply chain and many other aspects is required. The successful implementation of hydrogen-based systems requires active participation from governments, stakeholders, and society, supported by strong socioeconomic and institutional frameworks. All factors contributed significantly to the hydrogen economy, which should also be considered for further adaptive and mitigation actions at the local level. Therefore, future studies should consider these barriers as block factors that inhibit the success of hydrogen economy. Other factors also need to be evaluated in a robust behavioral change model to increase the society participation and build awareness in future hydrogen economy studies.

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