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Review

A Historical Analysis of Hydrogen Economy Research, Development, and Expectations, 1972 to 2020

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Abstract: Global climate change concerns have pushed international governmental actions to reduce greenhouse gas emissions by adopting cleaner technologies, hoping to transition to a more sustainable society. The hydrogen economy is one potential long-term option for enabling deep decarbonization for the future energy landscape. Progress towards an operating hydrogen economy is discouragingly slow despite global efforts to accelerate it. There are major mismatches between the present situation surrounding the hydrogen economy and previous proposed milestones that are far from being reached. The overall aim of this study is to understand whether there has been significant real progress in the achievement of a hydrogen economy, or whether the current interest is overly exaggerated (hype). This study uses bibliometric analysis and content analysis to historically map the hydrogen economy's development from 1972 to 2020 by quantifying and analyzing three sets of interconnected data. Findings indicate that interest in the hydrogen economy has significantly progressed over the past five decades based on the growing numbers of academic publications, media coverage, and projects. However, various endogenous and exogenous factors have influenced the development of the hydrogen economy and created hype at different points in time. The consolidated results explore the changing trends and how specific events or actors have influenced the development of the hydrogen economy with their agendas, the emergence of hype cycles, and the expectations of a future hydrogen economy.

Keywords: hydrogen economy; historical analysis; bibliometric analysis; sociology of expectations; hype cycle

Citation: Yap, J.; McLellan, B. A Historical Analysis of Hydrogen Economy Research, Development, and Expectations, 1972 to 2020. *Environments* **2023**, *10*, 11. https://doi.org/10.3390/environments10010011

Academic Editors: Shu-Yuan Pan, Daeseung Kyung, Cheng-Hsiu Yu and Yu-Pin Lin

Received: 21 November 2022
Revised: 23 December 2022
Accepted: 28 December 2022
Published: 6 January 2023

1. Introduction

The usage of hydrogen as an inexhaustible source of fuel was described in Jules Verne's 1894 novel "Mysterious Island" long before it was considered a possible solution to the energy crisis of the current era [1,2]. Despite hydrogen's flexibility and potential environmental benefits as an energy carrier, it is found only in minor concentrations in the lower atmosphere. It is most commonly bonded with other elements such as oxygen to form compounds such as water [3]. Hydrogen can be produced from diverse resources, from fossil fuel resources to renewable resources such as solar or wind energy [4].

John Bockris first coined the term "Hydrogen Economy" in 1972 to describe a future in which we use hydrogen as an alternative to fossil fuel [5]. The original vision of a hydrogen economy was conceptualized at a time when concerns about fossil fuel depletion in the face of exponential growth in global primary energy use and the associated rising pollution levels were being highlighted [6]. During this initial conceptualization of the hydrogen economy, hydrogen was conceived as playing the critical role of a universal energy carrier through which nuclear energy and solar energy could be produced and distributed economically [7,8]. In recent years, the role of hydrogen has expanded to provide the energy storage that would allow continuous base-load electricity supply in a system relying substantially on intermittent and variable renewable energy resources such as solar and wind energy [9].

Thus, the concept of a hydrogen economy can be described as the utilization of hydrogen as an energy carrier for different sectors complementing electricity.

Global events, most notably the concern over environmental degradation at the local scale and climate change at the global scale [10], geopolitical disruption of the energy supply [11], volatile fossil fuel prices [12], and recent growth of clean technology innovation [11] have reenergized sociological and economic interest in cleaner energy systems including options such as a hydrogen economy [13]. Ever since the term hydrogen economy was coined, the interest in hydrogen as an energy carrier and the hydrogen economy concept has periodically waxed and waned. In the past five decades, there have been multiple attempts to drive a global hydrogen economy, but the hydrogen economy has not yet happened to any significant extent, and enthusiasm declined [14]. Significant mismatches exist between the present situation surrounding the hydrogen economy and previous proposed milestones that are far from being reached. In 2016, Moliner, Lázaro, and Suelves [15] investigated a hydrogen roadmap published by The High Level Group for Hydrogen and Fuel Cells (HLG) for Europe from 2000 to 2050 and concluded that the proposed milestones for 2015 have not been met. Another example of mismatches is the projection of fuel cell vehicles (FCV). In 2004, HyNet Project [15] reported there would be half a million to one million FCV in Europe by 2015, while the Fuel Cell Commercialization Conference of Japan (FCCJ) [16] projected five million FCV in Japan by 2020 in their 2002 roadmap. However, IEA only reported over forty thousand FCV on the road globally in 2021 [17]. The latest interest wave has arisen as governments and energy companies have put hydrogen forward as a major candidate to decarbonize the economy, with extra momentum for post-COVID-19 recovery efforts [18]. The pandemic has devastated the global economy and many lives, but the recovery phase presents an opportunity for the energy sector to capitalize and pave the way for green hydrogen that complements renewables [19,20]. However, it is yet to be seen whether the current wave of interest will be different compared to previous attempts to drive a global hydrogen economy. Thus, the challenges are twofold: first, to measure the historical development of the hydrogen economy. Second, to identify how specific events or actors influence the interest in the hydrogen economy.

Approach and Its Novelty

In recent years, researchers in science, and historians, have shown a keen interest in understanding the potential of various streams of technological development [21–23]. While historical analysis [24] and technology forecasting [25] are not new, they have been used more extensively to explore different energy scenarios or identify possible barriers and drivers in today's society. Thus, there is a demand for studies that can forecast a future emergent technology's progress based on earlier expectations [26,27]. One of the key ideas leading to this type of research is the concept of hype.

The concept of 'hype' is widely used in mass media in a deliberate and exaggerated effort to attract people's interest [28]. Marketing practitioners recognize that hype generates attention and can influence diffusion patterns [29]. The Gartner Hype Cycle Model was developed based on this insight to track the development of technology versus its visibility. The hype cycle model tracks the development of a technology as it progresses through successive stages of peak, disappointment, and recovery of expectations [29]. The hype cycles of technological innovation are recognized as an integral part of the history of technology and not something that only exists in the initial development stages. Based on this perspective, it is possible to explore the nonlinear progress of how technological innovation is intertwined with expectations created by different historical actors [30,31].

Although the hype cycle model has gained substantial academic attention, case studies using the hype approach to explore technological transition have thus far remained limited. Studies that have used the hype approach are renewable energy [32], energy storage [33], and hybrid cars [34]. However, the hype cycle has not been used extensively to explore the development of the hydrogen economy. Presently, bibliometric analysis, literature review, and historical analysis have been widely used to analyze the development of the hydrogen economy. A comprehensive literature review and a summary table have been provided in the following Literature Review section.

Inspired by energy transition theory and socio-economic aspects of the hydrogen economy, this paper's aims are twofold: first, to present a historical analysis of the currently available hydrogen economy literature by combining content analysis and bibliometric analysis. Second, to describe a historical narrative of the hydrogen economy that clarifies the hype cycles and expectations of the hydrogen economy among different societal groups or actors. The novelty of this paper is using academic publications, mass media articles, and industrial projects to represent the hydrogen economy's development more completely. By quantifying and analyzing three sets of interconnected data, it is possible to examine the development of the hydrogen economy from multiple perspectives, starting from 1972, when the hydrogen economy was first coined, and up to 2020. This chronological approach contextualizes historically how specific events or actors have influenced the development of the hydrogen economy with their agendas, the emergence of hype cycles, and the expectations of a future hydrogen economy.

2. Literature Review

The history of the hydrogen economy, despite totaling only a few decades since its conceptual expression, can be seen to be complex and evolving. Pioneering authors in the field, Nejat Veziroğlu [35] and John Bockris [36], addressed the turbulent progress of the hydrogen economy from their firsthand experiences at different point of the hydrogen economy. As shown in Figure 7, Nejat Veziroğlu's article was published in 2000, when the previous wave of hype was rising rapidly, while John Bockris article was published in 2013, after the peak of the previous hype had died down. Despite the articles were published at different time, they concluded that the hydrogen movement had gained momentum over the years and would continue growing in the future. On the other hand, Hultman and Nordlund [37] used historical analysis to explore the expectations of fuel cells in promoting the realization of a hydrogen economy. Their study analyzed press articles, and government reports from 1990 to 2005 to characterize important events and actors influencing the hydrogen economy.

Using the standard literature review process, Solomon and Banerjee [38] surveyed government policies, industry reports, intergovernmental reports from 1998 to 2005 and concluded that although the hydrogen economy concept is more widespread, governments and companies alike had only vague plans for hydrogen development. El-Emam and Özcan [39] systematically reviewed 170 journal papers, analyzing the production cost of hydrogen by different production pathways. In a similar study, McDowall and Eames [40] conducted a systematic review by examining 40 case studies, including governmental policy, journal papers, and industrial reports, against a standard survey template to ensure the data were collected and compared consistently. Their results revealed that each actor group had a different image of a future hydrogen economy rather than a shared vision.

In recent studies, bibliometric analysis has been used to highlight the changing interest in a particular area of study, such as renewable energy [41], carbon capture & storage [42], electric vehicles [43], and also the hydrogen economy [44,45]. Tsay [46] investigated the characteristics of hydrogen energy publications and the implications by using bibliometric techniques on 14,449 journal papers (from 1965 to 2005). The results indicated that hydrogen energy research has grown exponentially and reinforced the idea that hydrogen energy has a major role in the future energy system. Yonoff et al. [47] investigated the research trends of fuel cell power generation systems using a bibliometric approach on 15,020 journal papers (from 2008 to 2018). A similar overview was presented by Alvarez-Meaza et al. [48], quantifying scientific and technological trends of fuel cell electric vehicle (FCEV) research by analyzing bibliographic information from journal papers and patents. Related to user perceptions of a hydrogen economy, Martin, Agnoletti, and Brangier [49] conducted a bibliometric analysis. As a result, end-users' acceptance was perceived as a barrier to developing a hydrogen energy system.

As bibliometric analysis inherently draws on an extensive data library, there is a possibility to miss relevant publications that did not use the related keywords in the data searching process [50]. Bibliometric analysis is ideal for assessing hundreds or thousands of publications based on metadata information but is more limited in comprehensively reviewing a publication individually [51]. This inherent limitation of bibliometric analysis can be countered by use in conjunction with a deeper qualitative analysis (content analysis or thematic analysis) or using multiple data streams (patent, mass media, governmental reports). Hence, it is worth noting that several authors have utilized both bibliometric analysis and content analysis to explore research trends and delve deeper into the literature [22,52,53].

A comparison table of the different studies, their methods, datasets, study period, and description of the study on the different aspects of the hydrogen economy is provided in Table 1. These studies address various aspects of the hydrogen economy, such as production, end-use application, and user perception.

Table 1. Summary of Literature Review—Studies analyzing hydrogen technologies and hydrogen economy progress.

Ref	Published in	Method	Data	Period	Description of Study
[35]	2000	Retold from experience	Mass Media	1972–2000	Progress evaluation of hydrogen economy's knowledge, technological development, and public awareness
[36]	2013	Retold from experience	-	1972–2012	Retelling of the contribution of early advocates of hydrogen economy and how it came about
[37]	2013	Historical Analysis	Press articles Government report Mass media articles	1990–2005	Establish the history timeline of development of fuel cell and expectation of fuel cell technology associated with the vision of a hydrogen economy
[39]	2006	Systematic review	170 journal papers	1970–2019	Analyze the production cost of hydrogen by different pathways important for near term deployment of large-scale hydrogen production
[40]	2019	Systematic Review	Government policies Journal papers Industry reports	1996–2004	Investigate expectations, drivers, barriers, and characteristics of different interpretations of hydrogen economy
[38]	2006	Literature Review	Government policies Industry reports	1998–2005	Survey the global status of hydrogen energy research, development, and different countries policy on hydrogen energy
[44]	2020	Bibliometric analysis	58,006 journal papers	1935 to 2018	Establish history timeline of hydrogen supply chain by analyzing bibliographic information of journal papers
[45]	2019	Bibliometric analysis	13,915 patents	1998–2018	Explore the research trend of hydrogen economy by analyzing bibliographic information of patents
[46]	2008	Bibliometric Analysis	14,449 journal papers	1965–2005	Quantify the growth of hydrogen energy literature by analyzing bibliographic information of journal papers

Table 1. *Cont.*

Ref	Published in	Method	Data	Period	Description of Study
[47]	2019	Bibliometric Analysis	15,020 journal papers	2008–2018	Explore the research trend of PEMFC by analyzing bibliographic information of journal papers
[48]	2020	Bibliometric analysis	2514 journal papers 1909 patents	1999 to 2019	Quantify scientific and technological development of FCEV by analyzing bibliographic information of journal papers and patents
[49]	2020	Bibliometric analysis	152 journal papers	1982–2018	Analyze end-user perception of a hydrogen economy by analyzing bibliographic information of journal papers

3. Material and Methods

To examine the development of the hydrogen economy from multiple perspectives, three sets of interconnected data are collected and analyzed: academic publications, media articles, and industrial projects. Figure 1 outlines the methodology used in this study.

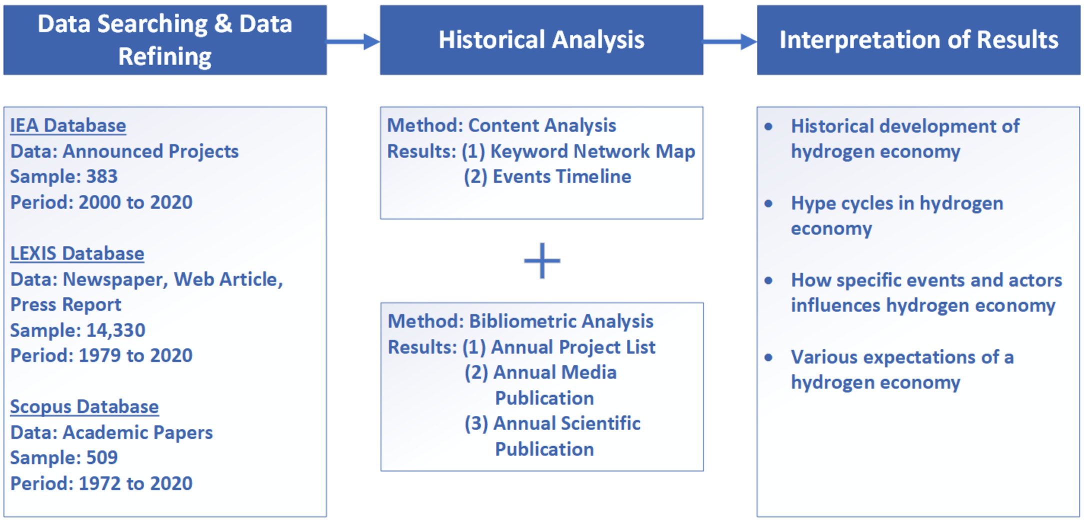

Figure 1. Research Methodology.

To evaluate research trends in the scientific community, Elsevier's Scopus was selected for this study as it is one of the largest databases of peer-reviewed academic literature. Although some studies show better results are obtained by using more databases (Scopus, Web of Science, Google Scholar), a high percentage of Scopus results are also found in Web of Science and Google Scholar [48]. To gauge the interest of society, the LEXIS database was chosen as it covers a wide range of international media, such as newspapers, press releases, industry news, and web publications. Several publicly available databases include the European Union's Fuel Cells and Hydrogen Joint Undertaking Projects, the United States Department of Energy Hydrogen Program, and the IEA hydrogen database. However, only the IEA database encompasses worldwide projects, and the coverage period is the longest (since 2001). The IEA database consists of government and privately funded projects to implement hydrogen production. Thus, the IEA hydrogen database was selected to evaluate industry perspectives [54].

In this study, the search query is important to capture the longitudinal dynamics of the existing body of knowledge. For example, "hydrogen energy system" was used interchangeably with "hydrogen economy" in the earlier period of development of the concept, so it is important to identify and include search queries that have similar meanings to "hydrogen economy". The search queries for Scopus and LEXIS databases are documented in Appendix A Table A1.

In the Scopus database, the data were retrieved using a title search and the period was from 1972 to 2020. Errata, letters, notes, and editorials were removed from the search results to focus on the core peer-reviewed literature. In total, 2009 potential studies on the hydrogen economy were obtained. Relevant studies were then filtered by examination of the title and abstract. Studies were included that described a hydrogen economy/energy system, pathways leading to a hydrogen economy, or hydrogen supply chain (production, transportation, distribution). As a result, a total of 509 studies were obtained. Although the dataset for this study is smaller than other bibliometric type studies, the selected studies can be argued to better represent the specific topic of the hydrogen economy due to the rigorous refining process. In the LEXIS database, the search was conducted on whole articles, and the period was from 1979, the earliest documented article, to 2020. A total of 11,125 articles were obtained. In the IEA database, only projects with timeframes are recorded. A total of 383 projects from 2000 to 2020 were obtained. Finally, a normalized annual publication graph was drawn for each dataset to track the historical interest in the hydrogen economy as shown in Figure 7.

The historical analysis depends on making use of the existing body of knowledge. This task is increasingly challenging to manage, given the exponential growth rate of published literature over recent years. However, with large-scale digital databases and powerful computer processors, researchers have used data mining to discover new information or linkages across extensive collections of articles. Although this technique cannot replace human interpretation in complex tasks, it can be used to quickly identify research gaps or construct a research timeline by analyzing large volumes of information. At present, keyword co-occurrence analysis is one of the most used methods by researchers to identify emerging research themes [41,43]. Keywords are represented by nodes, while the links represent the co-occurrence relationship between the keywords. The size of the nodes represents the number of times a keyword appeared in the collected studies. The association strength between the keywords defines the frequency of a pair of keywords co-occurring in multiple studies. The association strength describes the similarity S_{ij} between two nodes i and j as

$$S_{ij} = \frac{C_{ij}}{W_i W_j}$$

where C_{ij} is the frequency of nodes i and j co-occurrences while $W_i W_j$ is the total frequency of occurrences for nodes i and j. By determining the node's centrality and analyzing the strength and pattern of links between keywords, meaningful knowledge or insights can be uncovered [24]. Thus, the keyword co-occurrence network shows the cumulative knowledge network over a large volume of information [55]. For example, keywords can be associated with discovering specific events or leading topics in the research field.

Many studies [23,56] use an arbitrary number to adjust the keyword list based on appearance frequency, but this method may also cut off critical linkages between other keywords. To optimize the knowledge mapping visualization, keyword grouping is used to group related keyword clusters and reduce the total number of keywords. The keywords are grouped into a hierarchy system of topical and related specific keywords. For example, "natural disaster" is considered a topical keyword, while "tsunami" is a specific keyword. However, it is important not to group too many keywords under a topical group as this will lead to oversimplification of keywords and risk losing potentially useful information. This study conducted keyword co-occurrence analysis on Scopus case studies as author keywords, and Scopus index keywords could be readily retrieved. Generally, keyword co-occurrence mappings cover the study period, but the mapping can also be divided into regular time intervals. The mappings in this study are divided into decades (1972–1979, 1980–1989, etc.). This approach adds a chronological layer to the mapping and tracks the development of the hydrogen economy historically.

4. Results

By quantifying the extensive amount of qualitative material, a historical timeline can be created to help contextualize and examine how specific events or actors influence the interest in the hydrogen economy and the emergence of hype cycles.

4.1. The History of Hydrogen Economy by Keyword Mapping

Keywords are scientific terms that represent a summary of academic studies. 2166 unique keywords were extracted from 509 studies in the Scopus Database from 1972 to 2019. After data cleaning, 1003 unique keywords were categorized into 125 specific keywords under 11 topical themes, Table A2. In general, three development phases can be observed, a slow growth phase (1972–1979), a stagnant growth phase (1980–1999), and a rapid growth phase (2000–2019).

4.1.1. Slow Growth Phase (1972–1979)

During the slow growth period, 45 publications fitting with the scope of analysis were published in the 8 years, comprising 9% of the total analyzed publications. Hydrogen research only started to gain some recognition in the context of energy after the term "hydrogen economy" was coined by John Bockris in 1972. Before 1972, there was no official concept of the "hydrogen economy," and scientists were mainly focused on the practicality of hydrogen as a fuel. This is evident as the most central node is "hydrogen" instead of "hydrogen economy," as illustrated in Figure 2. The 1970s was a critical decade in the context of energy, in which the international energy crises (1973 oil crisis [57] and 1979 energy crisis [58]) started a search for a more resilient energy system, including options such as utilizing hydrogen. Hydrogen interest in this decade peaked in 1974 with the establishment of the International Energy Agency (IEA) and the International Association for Hydrogen Energy (IAHE). One of IEA's priorities was to respond to the global oil crisis by exploring alternative technologies such as hydrogen [59]. The golden age of nuclear power has widely been considered to span from the mid-1940s to the late 1970s before the Chernobyl Accident in 1986 [60]. In line with this, nuclear energy was widely considered as an option to produce abundant and cheap hydrogen in addition to electricity [61,62]. In this decade, environmental concerns were not the main motivation for a hydrogen economy.

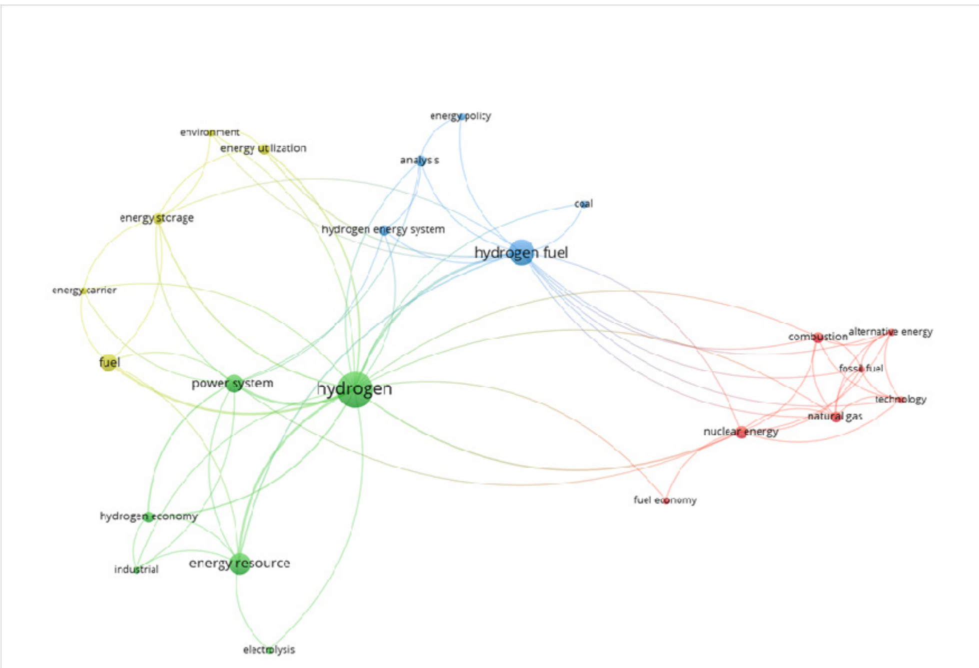

Figure 2. Keyword network map for 1972 to 1979.

4.1.2. Stagnant Growth Phase (1980–1999)

During the slow growth period, 37 publications fitting within the scope of analysis were published in 20 years, comprising 7% of the total analyzed publications. As indicated in Figures 3 and 4, although the number of publications decreased significantly, the network of keywords grew compared to Figure 2. The total number of papers and keywords for each period is documented in Table A3. During the 1980s, hydrogen research branched into several new areas, including using hydrogen as storage and producing hydrogen from solar energy and other alternative energy [63]. In Figure 3, the interconnection between the keywords of "solar energy," "hydrogen production," "energy storage," and "electrolysis" support this theory. The rising interest in cleaner energy may also be associated with the scientific community focusing on producing clean hydrogen from nonpolluting resources. However, during this decade, the low oil price hindered further development towards clean energy transition [64]. At the same time, the 1986 Chernobyl disaster reduced the attraction of the idea of production of hydrogen from nuclear energy.

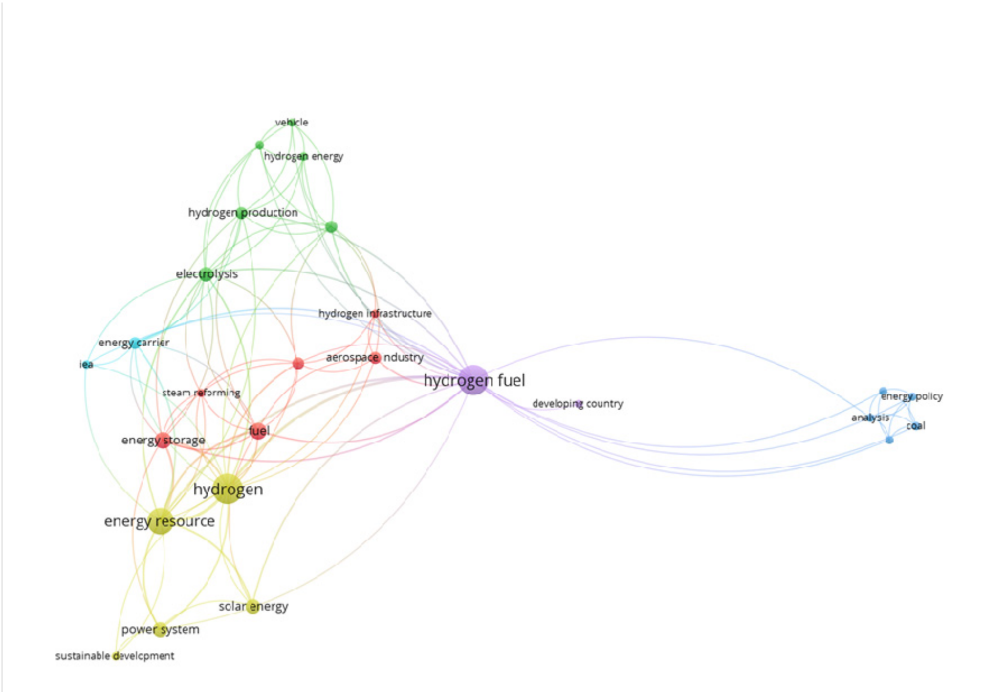

Figure 3. Keyword network map for 1980 to 1989.

Hydrogen research confronted a puzzling situation in the 1990s. Climate change gained enough attention to result in the United Nations Framework Convention on Climate Change (UNFCC) in 1992 [65] and subsequently the Kyoto Protocol in 1997 [66]. This can be associated with increasing keywords related to environmental concerns, as shown in Figure 4. The Kyoto Protocol had a significant impact on the development of clean energy, which also reinvigorated the vision of the hydrogen economy. Starting from 1998, the hydrogen economy publication trend accelerated, and 84% of publications were recorded after the signage of the Kyoto Protocol.

In 1983, Ballard Power Systems started investing in the development of fuel cells which later attracted Daimler Benz and Chrysler to develop the next generation of fuel cell vehicles [67]. In the following years, in the early 1990s, scientists managed to reduce the platinum in the fuel cell by one-tenth of its original amount and significantly reduce the cost of production [68]. However, the price of fossil-fuel-powered vehicles remained cheaper than fuel cell vehicles even with this major improvement.

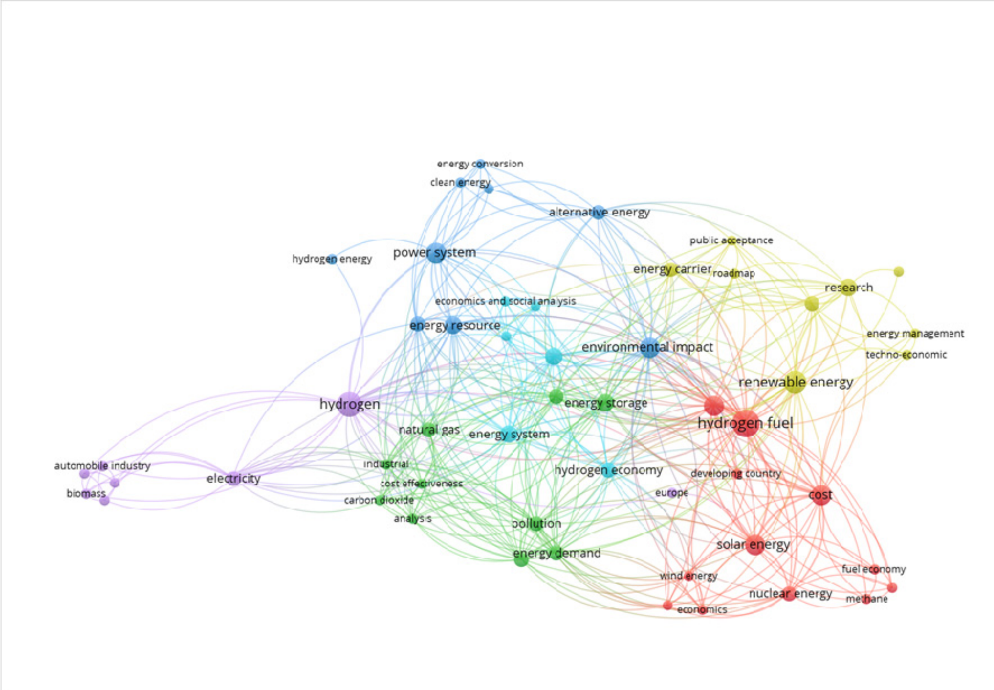

Figure 4. Keyword network map for 1990 to 1999.

4.1.3. Rapid Growth Phase (2000–2019)

Compared to earlier decades, hydrogen research was more developed and integrated with the exponential growth of publications and the emergence of new keywords and clusters. 430 publications were published in the last 20 year period, which constitutes 83% of the total publications. This sudden publication burst is also associated with the information era since the early 2000s [69]. Our knowledge library has been converted to a digital format which also streamlined the publication process to enable faster review and publication, as well as easier archiving and freer keyword selection.

The 2000s and 2010s have been considered the renewable energy era as renewable energy and related technologies grew significantly [70]. The annual global investment increased 10 times from 2003 to 2012. By 2012, renewable energy had overtaken fossil fuel and nuclear energy in global yearly investment [71,72]. As renewables grow, hydrogen became seen as an option to act as storage to solve the intermittency of renewables. The synergy between hydrogen and renewable energy can address the growing need for power system flexibility and clean energy production [30,71]. Hydrogen production with fossil fuels was still seen as relevant, but with CCS technology considered more important for carbon mitigation, particularly with a number of major hydrogen programs having a strong coal-based production focus [73].

Concerns over imported oil supply security have been looming ever since the first oil crisis, but the 11 September 2001 attack intensified this concern. As a means of diversifying the energy mix, the United States and the European Union launched a collaborative effort to accelerate the development of the hydrogen economy in 2003 and ultimately may have reenergized the interest in hydrogen-related research since then [74].

Starting in the mid-2000s, the demand for lithium increased significantly as a critical component for batteries in electronic devices and electric vehicles. In that period, the lithium-ion battery (LIB) price also dramatically decreased [75]. In addition, from 2011 to 2017, battery density has been improving at a rate of 7.5% a year, meaning battery packs will be smaller and last longer [76]. Hydrogen and LIB are regarded as competitors in many areas, so the advancement of LIB contributed to the reduction in interest in hydrogen technologies.

Additional causes for the 2010 publication decline could be linked to a lag effect of the 2008 global financial crisis (reduced research funding, etc.) [77]. The Fukushima accident in 2011 also decreased the public acceptance of nuclear energy, and nuclear relevant keywords were nowhere to be found. The ratification of the Paris Agreement in 2016 may have contributed to the renewed interest in hydrogen energy in subsequent years [78]. In addition, more keywords associated with climate change have increased due to climate concerns of the previous decade. The establishment of the Hydrogen Council (HC) in 2017, which unites the world's biggest oil companies and industrial players, has revigorated the hydrogen economy by drafting blueprints to enable the transition to a future hydrogen economy [79,80]. To realize the hydrogen economy transition, research is more focused on drafting policy and building infrastructure to facilitate this transition. As a result, "policy," "roadmap," and "modeling" keywords have appeared more frequently. This was also when "hydrogen economy" became the central of node, as shown in Figures 5 and 6. The uniqueness of the current hydrogen hype is the broadness of its base compared to the previous hype cycle when the discussion was focused on a specific area of hydrogen technologies.

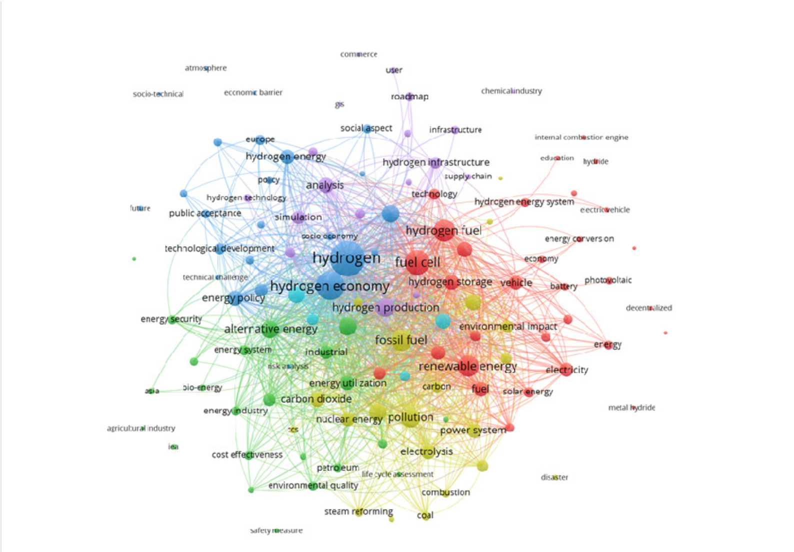

Figure 5. Keyword network map for 2000 to 2009.

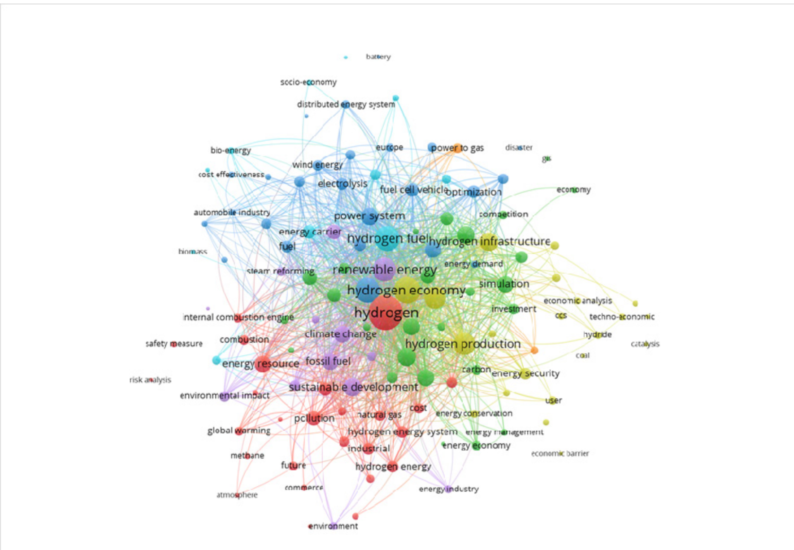

Figure 6. Keyword network map for 2010 to 2019.

4.2. Historic Interest in Hydrogen Economy

The analysis results, in the form of annual academic publications, mass media articles, and hydrogen-related projects, were normalized and then mapped chronologically against specific potentially relevant events to represent historical interest in the hydrogen economy, as shown in Figure 7. The three data sets were normalized across the range of occurrences, with the year of maximum occurrence set to 1 and minimum occurrence set to 0 to compare them on the same scale. From a quantitative perspective, interest in the hydrogen economy has significantly progressed over the past five decades based on the growing numbers of academic publications, media coverage, and projects. However, cyclical patterns have also been observed over the years, hereby referred to as the hype cycle. The upward trend represents an increase in interest toward a hydrogen economy, while the downward trend represents a decrease in interest.

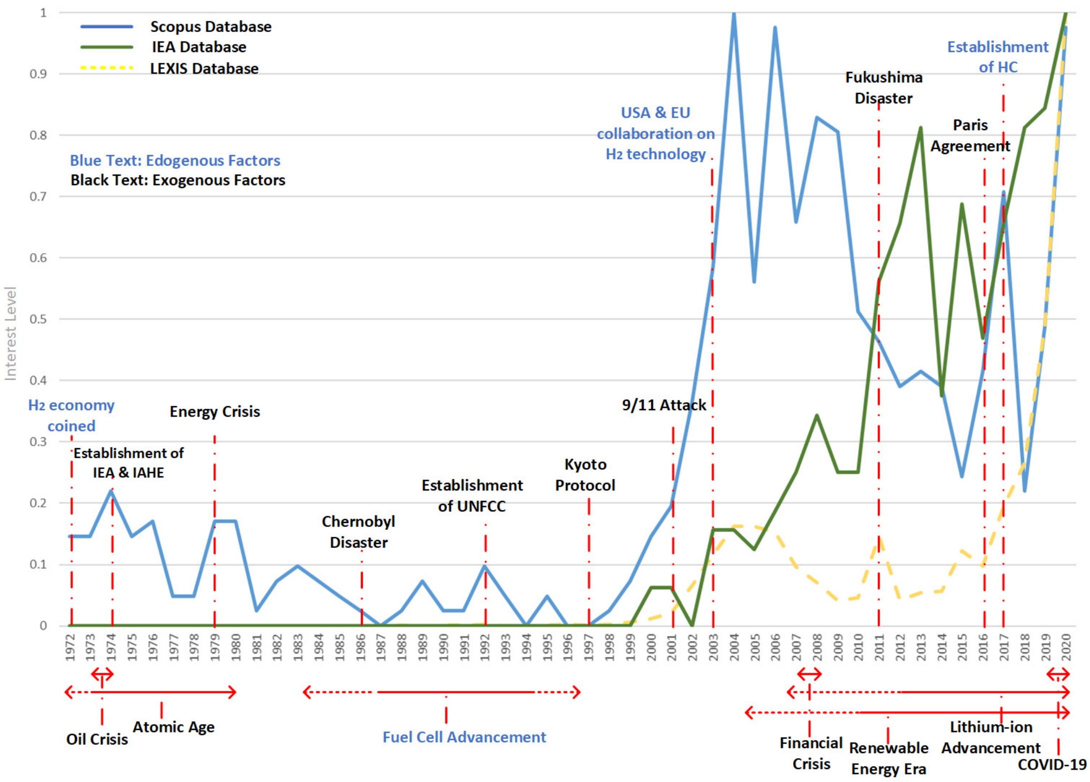

Figure 7. Normalized annual publications in selected literature.

Early stage innovations or technologies face challenges and barriers, but it may be argued that the hype cycles are more apparent in hydrogen-related technologies. Figure 8a shows the normalized annual journal publications of fuel cell vehicles (FCV) and electric vehicles (EV) retrieved from the SCOPUS database, while Figure 8b shows the normalized annual articles on fuel cell vehicles (FCV) and electric vehicles (EV) retrieved from LEXIS Database. By comparing the trends for FCV and EV, it is apparent that the FCV graph shows more peaks and troughs, despite an overall increasing trend across the period. We consider this as an indication of hype cycles, in which attention to hydrogen technologies peaks and wanes. On the other hand, EV progress and attention has been progressing at a much steadier rate. The difference may be that while EV have progressively made their way into the market, with improvements in range and accessibility of infrastructure, as well as decreases in cost, FCV have offered a seemingly attractive alternative but have not delivered the foreseen benefits or uptake. In the academic literature, such trends can of course follow trends in funding, which may be directly or indirectly related to societal uptake of a given technology.

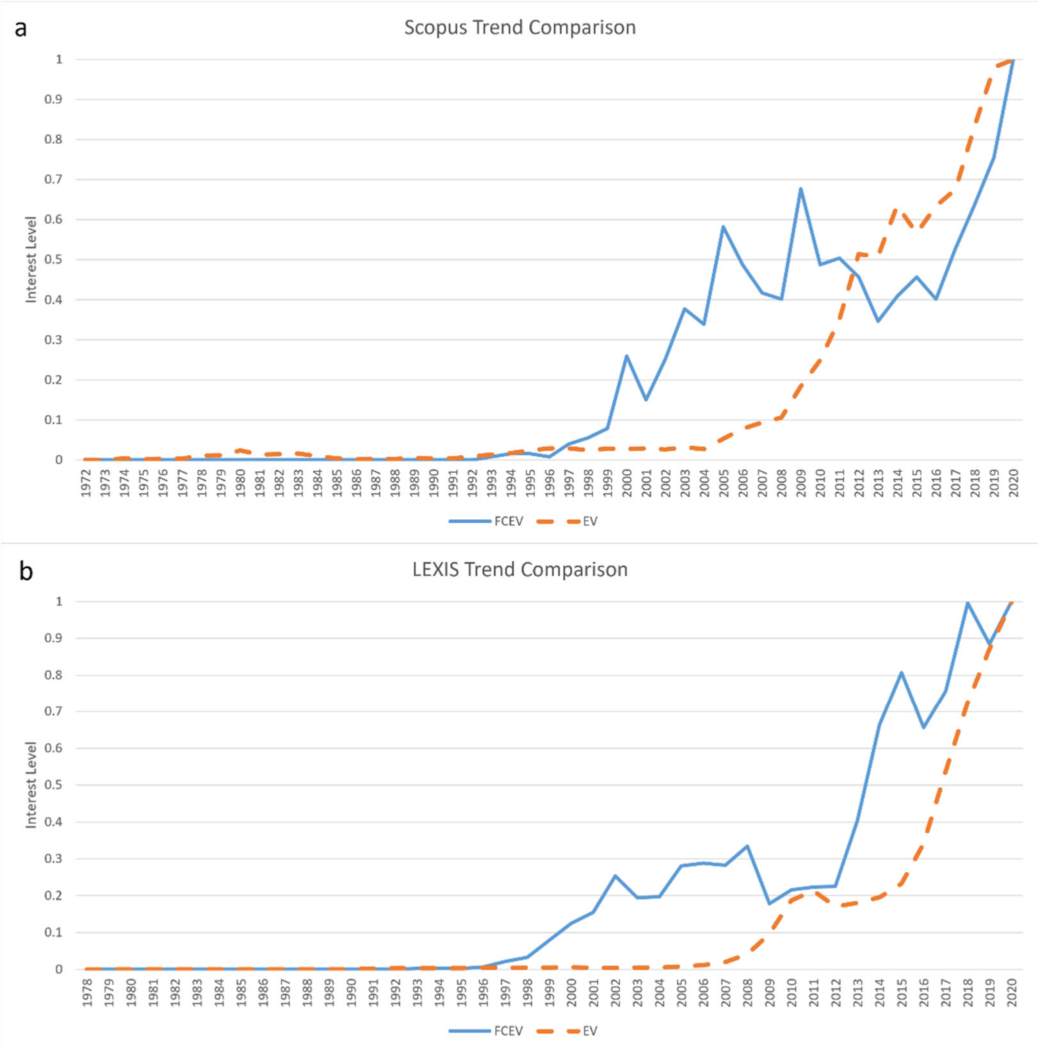

Figure 8. Trend Comparison between FCEV & EV (**a**) Normalized annual publications from SCOPUS (**b**) Normalized annual publications from LEXIS.

The historical interest in the hydrogen economy as an emergent concept has followed the trend of the hype cycle. The hype cycle represents a relationship between technology maturity and its visibility [81]. In academia, scholars refer to the concept of hype as a rapid increase and subsequent decrease of societal interest in transition studies [32,33]. The hype cycle can be associated with endogenous and exogenous factors acted upon by individuals, societal groups, industries, and organizations. Furthermore, factors can be divided into the trigger and long-term events. It is difficult to precisely identify the starting point of long-term events as its development is a gradual process. Hence, the development phase is marked by dotted lines, while a solid line marks the expansion era as illustrated in Figure 7.

Endogenous factors are influences that actors have some control over and directly impact the interest in the hydrogen economy. For example, pro-hydrogen organizations such as the International Association for Hydrogen Energy (IAHE) and Hydrogen Council (HC). Supporting policies such as national roadmaps for hydrogen and international commitments to hydrogen can also increase the interest and visibility of the hydrogen economy. The advancement of electrolyzer and fuel cell technology positively affects the interest in the hydrogen economy. In contrast, ambitious technological targets that are not met will bring down the interest level and public confidence.

Exogenous factors are events or circumstances that actors have no control over, which indirectly impact the interest of the hydrogen economy. For example, unforeseen economic conditions such as financial crises or energy crises. Clean technological advancements such as renewable energy technologies positively impact the hydrogen economy, while the advancement of electric vehicles and lithium ions may damper the progress of the hydrogen economy as a competing technology. Social ideology such as environmental movements motivates society to adopt cleaner technologies, influence the establishment of various environmental institutions, and ratify international treaties on climate change. These are only a few examples of exogenous factors, but the driving force of the hydrogen economy can be associated with such factors within or outside the boundary of the system.

5. Discussion

The transition to a hydrogen economy requires the involvement of various actors from different societal realms in offering their knowledge and resources to address the diverse aspects of the ongoing transition. The consolidated results can serve as an essential reference to understanding the dynamic interplay, including the involved actors' roles, agendas, and expectations of the hydrogen economy.

5.1. The Roles of Actors in Energy Transition

A sustainable energy transition requires technological innovations and the collaboration and participation of actors at different levels of society [82]. By applying the societal typology in Fischer and Newig's review [83], four main actors in different societal realms are identified: policymakers, industry, academia, and members of society.

The energy sector is key in leading the way to a zero-emission society with technological breakthroughs and rapid cost reduction. However, it could be faster if driven by institutional frameworks. By setting ambitious targets and goals, more investors, scientists, and cities are challenged to advance. At the institutional level, policymakers govern the energy transition through regulatory frameworks and policy solutions [84]. It has been argued that initiatives toward transitions mainly depend on what society demands. Still, policymakers can promote the reinforcement of a sustainable transition in institutional frameworks which can provide the necessary guidelines to foster the development and diffusion of technological innovations.

At the intermediate level, industrial sectors such as steelmaking, chemical, and aluminium manufacturing are the main contributors to carbon emissions due to their inherent requirement for large amounts of energy. Energy-intensive sectors that are unable to decarbonize via direct electrification are considering the prospect of using hydrogen as a more carbon-neutral alternative. The required technologies may exist but are not always the most cost-effective choice. Thus, policymakers and industry must work together to create a market mechanism based on institutional policies to counter competitive disadvantages and simultaneously deliver necessary changes in carbon emissions from the industrial sector [85].

Academia has a mediating role by providing and distributing the necessary knowledge, information, and technologies between institutions, industry, and society [86]. For example, researchers across disciplines can share their expertise with policymakers to understand how science can help design better policies to tackle environmental pollution, improve energy efficiency, and support the transition to a zero-emission society, while at the same time educating society on the importance of solving environmental and energy issues.

At the societal level, citizens are empowered when they play an active role in the discussions, decision-making, and implementation of projects or policies affecting them [83]. For example, the participation of the society in the development of institutional frameworks via functions such as reviewing and providing feedback on current guidelines. When sustainability becomes a key component of societal demand, the market and policy solutions will reshape the current and future energy landscapes.

In energy transition, actors can either be supporting or opposing forces relative to the transition under consideration. There are always forces that support or oppose the development of the hydrogen economy. For instance, while hydrogen supporting policies and international commitments have a positive effect, lobbying pressure from traditional energy companies wanting to maintain the status quo has a negative effect. The adoption of hydrogen technologies will be supported by some [87,88], while others will criticize the reliability of hydrogen-based technology in favor of competing technologies such as batteries [89]. Another example is industry actors, whose position depends on their business agenda. By evaluating each technology's strengths and weaknesses, companies can either diversify their business strategies with new technological developments or stick with established technologies to oppose development. Understanding actors' roles and agendas can help classify them as supporting or opposing forces. The power balance between the two coalitions can influence decisions, investments, processes in the ongoing energy transition [90].

Building on the above, a conceptual framework has been adapted from [32] to describe the power balance between competing actors and their influences, as shown in Figure 9. Actors in each coalition are engaged in narrative work and share their respective views, disseminating information based on their expectations for a hydrogen economy. Kriechbaum et al. [32] suggested that hypes cycles are driven by such narrative works and exemplified by discursive struggles between competing views on the respective technology. Specific events create space and allow supporters and opposers to share their expectations. Recent socio-technical transition studies have emphasized the role of specific events in hype cycles' emergence [32,33]. Hype cycles can be influenced by trigger events and long-term events over a more extended period, which may be seem to some extent in Figure 7. Endogenous events, such as technological breakthroughs and supporting policies, have a positive impact. The changes in the wider socio-technical economic content, characterized as exogenous events, play important roles too. For instance, advancement in competing technologies, financial crises, and changes in society's sociological and economic interest.

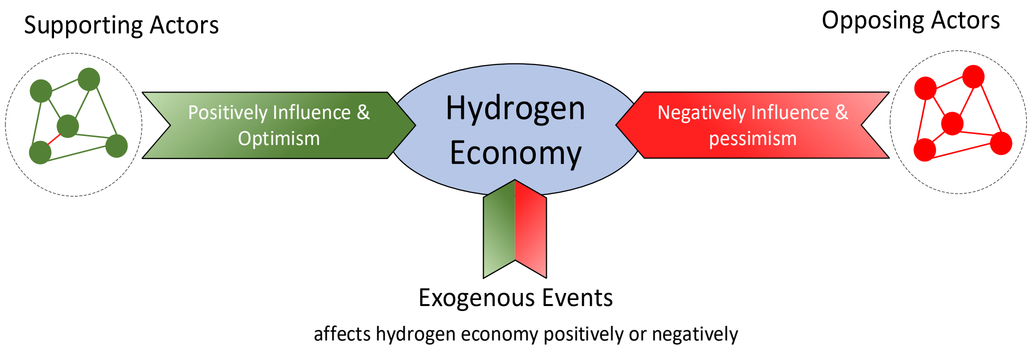

Figure 9. Conceptual framework of the influences towards hydrogen economy.

5.2. Expectations of the Hydrogen Economy

The hydrogen economy has attracted the attention of many and fostered great expectations. However, it is important to note that each actor operates in different societal realms with their own agendas or preferences, which may positively or negatively influence the development of the hydrogen economy. As in the parable of blind men and an elephant, many people interpret the hydrogen economy differently. However, each actor's different yet overlapping expectations have created somewhat of a shared concept of hydrogen economy which is flexibly interpreted as to what a future hydrogen economy may look like. This study draws on the work of Borup et al. [31], Van Lente [91] and Brown and Michael [26] to describe expectations as future-oriented abstractions that fuel the creation of opportunities and hopes, technological developments, economic growth, and also some kind of shared concept or image of what is to be expected.

A shared concept is vital to create common ground for emerging technology and innovation to develop freely [30]. Common ground will allow actors with different agendas to work and collaborate. Expectations play an important role in mobilizing resources at various levels, for example, at the institutional level by national policy regulation, at the intermediate level by collaborative efforts between institutions, and down to the individual level in the work of an engineer or researcher. As such, expectations can be seen as a bridge to mediate across different actors at different levels of societal realms. Historically, expectations tend to change over time, especially over a longer timeframe, in response to new conditions or issues, evolving social ideology, and the advancement of technology. As a result, hype cycles are a frequent occurrence due to the dynamic structure of expectations. As shown in Table 2, this study will highlight the difference in interpretation based on each actor's historical narrative and motives as an example of such perspectives.

Table 2. Summary of actors and their interest in hydrogen economy.

Actor	Interest in Hydrogen Economy
Energy Companies	Focus on blue hydrogen production to make use of existing fossil fuel assets in a transitional period to clean energy future
Environmentalists	Focus on green hydrogen production to bring down production cost and combat climate change issues
Financial Institutes	Capitalize hydrogen economy as new business opportunities by combining economic growth and hydrogen technology

In hydrogen production, there has been a division between methods that use fossil fuels and those that use renewable energy. Among the most prominent advocates of the hydrogen economy are the oil and gas industry companies, which have in some cases rebranded themselves as energy companies. As environmental concerns increase, energy companies are trying to determine ways to extract value from their stranded assets in the energy space, leading to an interest in blue hydrogen. Almost all energy companies have announced plans or roadmaps utilizing blue hydrogen as an intermediate phase before transitioning to green hydrogen [92,93]. Blue hydrogen is hydrogen produced from fossil carbon fuels coupled with carbon capture & storage technology. In contrast, green hydrogen is hydrogen produced by electrolysis from renewable sources by breaking down water molecules into oxygen and hydrogen. The utopian image of carbon-free energy is usually associated with green hydrogen. However, some energy companies are suggesting a transitioning period where hydrogen is derived from fossil fuels, then switching to blue hydrogen, and finally to green hydrogen as electrolyzer technology becomes cost competitive. This initiative is backed by fossil fuel lobby groups and some of the world's largest oil and gas companies. However, this transitioning phase poses a threat to green hydrogen production as the high investment cost of blue hydrogen infrastructures will result in a phenomenon called technology lock-in. Large-scale projects require many years and funding to be built, and they are designed to last for decades. The fossil fuel lobby group does not often mention this but is constantly argued by an environmental group and green hydrogen advocates [94,95]. Most notably, Corporate Europe Observatory, in a 2020 report, criticized the fossil fuel lobby group for undermining the true goal of the hydrogen economy, which is hydrogen produced by clean energy sources [96].

On the other end of the spectrum, environmental groups and like-minded people believe that blue hydrogen is delaying the transition, and green hydrogen should be the only way forward [97,98]. For green hydrogen to move from commercialization to dominance, investment and effort should be started now instead of later. This is to achieve economy of scale and bring down the cost of manufacturing electrolyzers, which in turn lower the cost of green hydrogen, just as how Tesla was able to revolutionize electric vehicles in the 2010s by focusing on the development of lithium-ion batteries [99,100].

Amid the blue hydrogen and green hydrogen debate, financial institutes have realized the opportunity to combine economic growth with environmentally friendly technologies and adopted hydrogen technology in their business ventures. Many of the world's biggest companies have shifted their focus to capitalize on this untapped market [3,101,102].

Energy companies envisioned hydrogen economies driven by natural gas [93,103,104], environmentalists envisioned hydrogen economies to counter climate challenges [72,105], and economists envisioned hydrogen economies as new business opportunities [106,107]. However, expectations are created in different contexts such as different settings, actors, points in history, and locations but may be connected in various ways.

The hydrogen economy can be seen as a wider transition towards a low carbon society or a 100% renewable energy concept in its broader conceptualization. The flexibility of hydrogen as an energy carrier allows it to be fitted into any future scenarios, whether it will be a renewable dominant energy mix or a resurgence of the nuclear power industry. Hydrogen may be the ideal candidate to solve the intermittency of renewable energy and the abundance of nuclear energy by acting as an energy carrier complementing electricity. To sum it up, the hydrogen economy is positioned within this interconnecting web and constantly evolves.

Despite the difference in interpretations, each actor is advancing on believing that the hydrogen economy will offer technological solutions to environmental and economic issues. This same message was repeated among different actors and passed on to society, creating a hydrogen hype [20,68]. However, more often than not, this utopian image of a hydrogen economy was being communicated without considering the complex history or technological barriers. There are major mismatches between the present situation surrounding the hydrogen economy and previously announced milestones that are still far from being reached [15]. Articles focus on how hydrogen technology will fit into future energy systems rather than how to roll out the technology realistically. This optimistic view created an unrealistic and unbiased expectation which will subsequently lead to the downfall of the hydrogen hype.

As evident in Figure 7, various endogenous and exogenous factors have influenced the development of the hydrogen economy and created hype at different points in time. Each hype comes with the expectations that the hydrogen economy is on the verge of a breakthrough and would be the ultimate solution for climate change. Despite the previous false start, advocates still believe in the utopian image of the hydrogen economy. Journalists kept reporting hydrogen-related articles, politicians adopted hydrogen technology as their environmentally friendly policies, publications on hydrogen were growing, and industry unveiled prototypes at every exhibition. This blinded enthusiasm goes together with the belief that, sooner or later, everything will fall into places like breakthrough or mass production. With each new hype cycle, actors deny or forget the downfall of previous hype and discuss the last development to fit into a linear narrative of progress. The lack of sense of history can be observed in mass media or hydrogen roadmaps. Most media ignore the complicated history and report about the next big thing while roadmaps are being rebranded with new targets with every release. This is contributed mainly by our growing internet library, in which history has been buried.

However, it is important to note that transition is often nonlinear progress, and previous hypes are recognized as an integral part of history. Although roadmap targets are mostly overshot, technological progress is still being made. The efficiency of both fuel cells and electrolyzers are increasing, while the costs are decreasing. Technologists who advocate upcoming technology tend to overestimate performance and cost targets while underestimating actual progress. In the past, society was pessimistic about the growth of renewable energy as it failed to deliver its promises due to inflated expectations [70]. Now, renewable energy, especially solar and wind, has grown rapidly, and most renewable energy technologies exceed their targeted cost and performance [108]. The hydrogen economy and its technologies face similar obstacles as its predecessors before global acceptance can be gained.

6. Conclusions

This study analyzed and visualized three sets of interconnected data combining content analysis and bibliometric approach to systematically establish the historical narrative of the development of the hydrogen economy mapped against chronological key events. In what ways do historical events impact on the development of hydrogen economy? What lessons can be gained from previous hype cycles in in shaping future energy scenarios? Addressing these questions within the hydrogen economy concept can provide insights that can be used for future energy transitions. Previous research on the development of the hydrogen economy focuses on the early stages of technological innovations to explore how expectations shape future energy scenarios. In this study, previous hype cycles are recognized as an integral part of the history of technology and not something that only exists in the initial development stages. Specifically, it can be argued that hype cycles emerge from specific events (within or outside of the hydrogen economy) fueled by competing actors with their agenda. Although significant mismatches exist between competing coalitions of actors, hydrogen is still generally agreed to play an essential role in future energy scenarios. Still, it should not be thought to do so in dominance but rather complementary with other energy carriers. Within the supporting coalition of actors, the expectations of a hydrogen economy can become contested and open to multiple interpretations. The different yet overlapping expectations of each actor have created a sort of shared concept of hydrogen economy yet flexibly interpreted of what a future hydrogen economy may look like. A shared concept is important to create a common ground for actors with different agendas to work and collaborate.

The past is linked to the present by a continuous chain of events. By understanding the past narratives of the hydrogen economy through the theoretical concept of actor's roles in transition and sociology of expectations, researchers and policymakers alike can better work towards a common hydrogen economy. In a 2021 report [4], IEA noted that there had been many false starts on the emergence of a global hydrogen economy in the past; and believe the current wave of interest could be different, with global efforts to reduce carbon emissions and transition to a cleaner future. Despite the optimistic outlook, it is yet to be seen whether the current wave of interest is another period of hype or, finally, the emergence of an operating hydrogen economy. Thus, assessing the current perspectives of society on a hydrogen economy is important to understanding social support, align our expectations of the hydrogen economy, and track our current progress toward a future hydrogen economy. Further work to investigate this through community and expert surveys is currently underway to help contribute to this understanding.

This study encountered several limitations that should be considered in future studies. The keyword co-occurrence analysis relied on article keywords (either from authors or Scopus) to historically map the development of hydrogen economy due to analyzing a large amount of data. As a result, the analysis reflects how authors and Scopus summarized the articles using keywords. The absence of some keywords may reflect a lack of research on that topic, but it could also reflect relevant topics caused by coordination problems in assigning suitable keywords. In addition, the social aspects of the hydrogen economy need to be examined to address the current understanding gap between different realms of society and people's preferences and perceptions towards the acceptance of using hydrogen as part of their daily lives. A sustainable transition to a hydrogen economy will require governance structures that are both participatory and inclusive, which empower all members of society to become full stakeholders in sharing its benefits.

Author Contributions: Conceptualization, J.Y.; methodology, J.Y.; investigation, J.Y.; data curation, J.Y.; writing—original draft preparation, J.Y.; writing—review and editing, J.Y. and B.M.; visualization, J.Y.; supervision, B.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Search query for SCOPUS and LEXIS database.

SCOPUS Search Query
TITLE ((“Hydrogen” “Economy”) OR (“Hydrogen” “Society”) OR (“Hydrogen” “Roadmap”) OR (“Hydrogen” “Future”) OR (“Hydrogen” “Energy Carrier”) OR (“Hydrogen” “Energy Source”) OR (“Hydrogen” “Energy System”))
Related Figure: Figure 7
SCOPUS Search Query
TITLE ((“electric vehicle”) AND NOT (“fuel cell”))
Related Figure: Figure 8a
SCOPUS Search Query
TITLE ((“fuel cell vehicle” OR “fuel cell electric vehicle”))
Related Figure: Figure 8b
LEXIS Search Query
(“Hydrogen Economy”) OR (“Hydrogen Society”) OR (“Hydrogen Roadmap”) OR (“Hydrogen Future”) OR (“Hydrogen Energy Carrier”) OR (“Hydrogen Energy Source”) OR (“Hydrogen Energy System”)
Related Figure: Figure 7
LEXIS Search Query
(“electric vehicle”) AND NOT (“fuel cell”)
Related Figure: Figure 8a
LEXIS Search Query
(“fuel cell vehicle” OR “fuel cell electric vehicle”)
Related Figure: Figure 8b

Table A2. Topical themes and specific keywords in keyword co-occurrence analysis.

Topical Theme	**Keywords**					
Actor	aerospace industry	agricultural industry	asia	automobile industry	chemical industry	developing country
	energy industry	europe	iea	industrial	international	user
Environmental Issue	atmosphere	cabon dioxide	climate change	decarbonization	disaster	environment
	environmental impact	environmental quality	global warming	pollution		
Economy/Market	commerce	competition	cost	cost effectiveness	economic barrier	economic impact
	economics	economy	energy economy	fuel economy	investment	marketing
Fossil Fuel Technology	coal	combustion	fossil fuel	internal combustion engine	methane	natural gas
	petroleum	steam reforming				
Energy	electricity	energy	energy carrier	energy resource	fuel	primary energy
Energy/Clean Technology	alternative energy	bio-energy	biomass	clean energy	hydropower	nuclear energy
	renewable energy	solar energy	wind energy			
Clean Technology	battery	catalysis	ccs	decentralized	distributed energy system	electric vehicle
	hybrid car	photovoltaic	power to gas			

Table A2. *Cont.*

Topical Theme	Keywords					
Hydrogen Economy	electrolysis	fuel cell	fuel cell vechile	hydride	hydrogen technology	metal hydride
	hydrogen	hydrogen economy	hydrogen energy	hydrogen fuel		
	hydrogen energy system	hydrogen infrastructure	hydrogen production	hydrogen storage		
Planning & Policy	decision making	energy conservation	energy conversion	energy demand	energy efficiency	energy management
	energy mix	energy policy	energy security	energy storage	energy system	energy utilization
	infrastructure	policy	power system	public acceptance	roadmap	socio aspect
	supply chain	supply demand	sustainable development	technical challenge	transition	transportation
Research & Development	economic analysis	economic and social analysis	risk analysis	socio-economy	socio technical	techno-economic
	gis	life cycle assessment	optimization	research	safety measure	simulation
	technological development	technology				
General	carbon	education	future	metal	vehicle	

Table A3. Summary of keyword co-occurrence analysis.

Time Period	No. of Paper	Total Keywords	Total Unique Keywords	Related Figure
1972–1979	45	83	24	Figure 2
1980–1989	25	78	27	Figure 3
1990–1999	14	113	54	Figure 4
2000–2009	251	2317	122	Figure 5
2010–2019	174	2072	124	Figure 6

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