Imagining a hydrogen economy

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Imagining a hydrogen economy: From grand technological utopia to enabler of the energy transition in three waves since the 1970s

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ABSTRACT

Conceptions of a future hydrogen economy have undergone a significant evolution over the past 50+ years. This study identifies three distinct 'Waves', or periods of high expectations for a hydrogen economy. The First and Second Waves were followed by declining optimism; the Third Wave is ongoing today. The three Waves are analyzed through a multi-method literature review, and we specifically analyze the First Wave through key historical sources and contextual analysis. We argue that the hydrogen economy emerged in the 1970s as a techno-utopian narrative within the scientific community, where hydrogen was envisioned as the ultimate energy carrier, driven by nuclear energy. Characteristics of the techno-utopian narrative include utopian terminology, dystopian future images, and neglect of negative side effects. During this period, the hydrogen economy did not develop beyond the conceptual phase. The Second Wave, starting in the mid-1990s, witnessed a resurgence of interest in hydrogen, particularly in the mobility sector. Governmental support and media portrayal fueled public enthusiasm, but practical challenges and misleading information resulted in disillusionment with the hydrogen economy ideal by the late 2000s. Today, in the Third Wave, hydrogen is repositioned as an energy vector for a more sustainable future, primarily as a carrier of (variable) renewable energy sources. Lessons from earlier Waves emphasize the importance of affordable renewable energy for hydrogen production, realistic objectives, a developed hydrogen infrastructure, and cross-sector collaboration. By addressing these elements, the Third Wave can avoid past pitfalls and advance hydrogen's role in a sustainable energy future.

1. Introduction

Hydrogen is frequently mentioned as a key component of the renewable energy transition [2–4]. International organizations, governments and companies have formulated extensive hydrogen strategies in recent years [3,5]. Hydrogen is regarded as a future vector for energy transport, a (seasonal) renewable energy storage option, feedstock for (heavy) industry, and as fuel for (heavy) transport [5–8].

The properties of hydrogen have been understood for centuries. Jules Verne famously mentioned it in 1874 as "an inexhaustible source of heat and light, of an intensity of which coal is not capable" ([9], ch.11). While visionary, this proposal was purely speculative, lacking concrete plans or ambitions. It qualifies as a pre-conceptualization at best. In the course of the 20th century, hydrogen fuel cells were developed for multiple applications. The idea of hydrogen as the cornerstone of an all-encompassing new energy system was first developed in the early 1970s, half a century ago. In this paper, we will look at its origins and draw some lessons for the present.

The hydrogen economy has not evolved linearly over time: periods of high expectations alternate with periods of lessening excitement. Using a basic analysis of publications related to the 'hydrogen economy' we have identified three distinct 'Waves'[1]: a First Wave in the 1970s, a Second Wave during mid-1990s to late-2000s, and a renewed Third Wave of interest in the late 2010s that is still ongoing (Figs. 1 and 2). These Waves serve as the framework for our analysis across various

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[1] We define a 'Wave' in the context of the hydrogen economy as a distinct phase of interest, technological progress, and societal engagement with hydrogen as an energy solution for problems that affect society. Each Wave is characterized by specific drivers — ideological, social, technical, economic — and represents a period in which hydrogen is viewed as a potential transformative force. Waves emerge, evolve, and recede over time, often shaped by shifting socio-economic contexts. The trajectory of each Wave resembles elements of the Gartner hype cycle [1] and is marked by stages of heightened optimism, and setbacks, reflecting the complex, non-linear journey towards potentially realizing a hydrogen economy.

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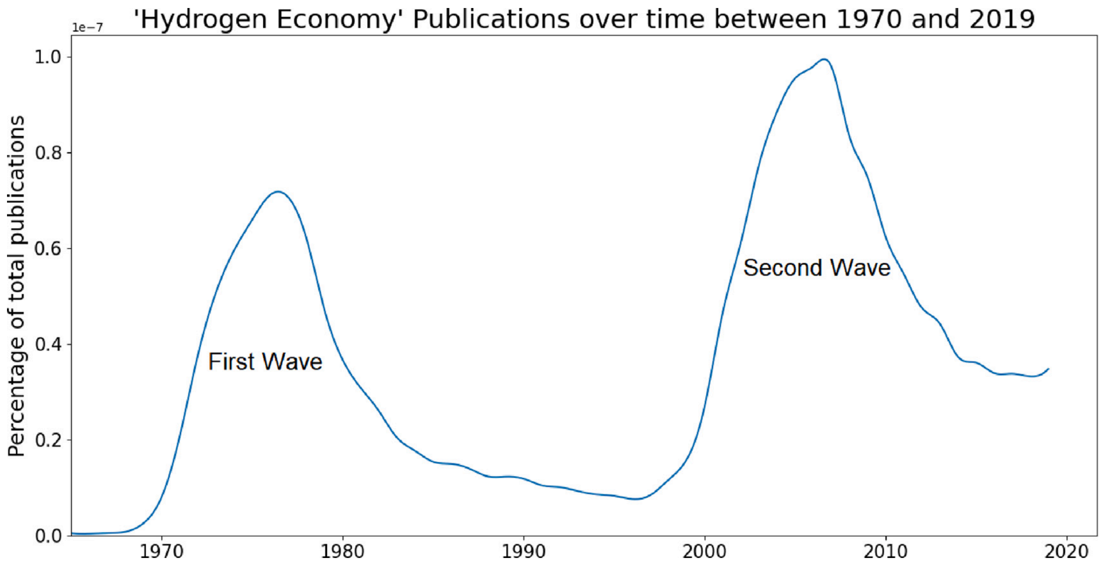

Fig. 1. Visualization of the percentage of works published based on the Google digitized publication database with "hydrogen economy" in the title. The image was derived from the database provided by Google Books Ngram Viewer tool. The database, which goes up to 2019, includes publications as a percentage per year of the total collection of books, journals, and other texts that Google digitized [10].

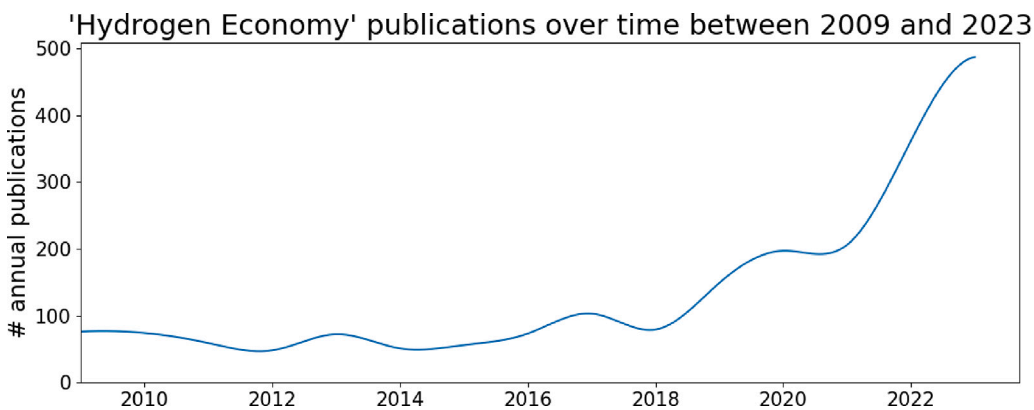

Fig. 2. Visualization of the total scientific publications in absolute numbers in the Web of Science database with "hydrogen economy" in the title, abstract or as keyword to highlight the resurgence in interest in hydrogen economy research [11].

time periods.

While the history of the Second Wave has been extensively analyzed [12–14], the First Wave has so far received little scholarly attention from historians. For that reason, the first part of this paper aims to analyze the development of the First Wave. We offer a qualitative analysis and contextualization of four key publications from the early 1970s [15–18]. Our study aims to understand how and why the hydrogen economy vision emerged in that specific historical context, and why it attracted so much attention and support within the scientific community. We argue that the concept of the hydrogen economy in the First Wave is best understood as an 'imaginary' with characteristics of a 'techno-utopian narrative'. These concepts will be introduced and explained in Section 3.

Although our primary focus is the emergence of the hydrogen economy vision within the scientific community, this study also seeks to bridge historical insights with contemporary discussions on hydrogen energy. The historical context has received too little attention within contemporary hydrogen economy research and strategy formulation. By exploring elements from the First Wave, we gain insights from this early period that can inform future research and guide informed decision-making, thereby supporting the advancement of the hydrogen economy. Such historical lessons may lead to more effective strategic choices, promoting hydrogen's role in achieving a sustainable energy system and mitigating the impact of climate change.

As interest in the hydrogen economy has broadened beyond the scientific community to involve a wider range of societal stakeholders, it is crucial to consider the socio-political and economic contexts that now shape its trajectory. In Section 7, we explore the continuities and discontinuities across the 50-year evolution of the hydrogen economy and examine how lessons from the First and Second Waves might inform the development of the Third Wave.

2. Three Waves

The First Wave finds its origin by the seminal paper by John Bockris and John Appleby from 1972 [15]: *The Hydrogen Economy: An Ultimate Economy?*, in which they state that:

> [..] the medium of energy between the necessarily remote future energy producing sites and population centers *should not be electricity, but hydrogen*, this hydrogen being converted to electricity on use-sites, or alternatively being used as such (e.g., for heating, and for chemical processes). ([15], p.31).

In the same year, Bockris added in a very short article in Science journal: "The term "hydrogen economy" applies to the energetic, ecological, and economic aspects of this concept". ([19], p.1323). Bockris provided examples of these aspects, such as the potential for hydrogen-powered fuel cells to propel various types of vehicles, reduced air and heat pollution when using hydrogen and fuel cells instead of fossil fuels, and significant cost reductions for the chemical and metallurgy industries [19].

The hydrogen economy was based on the premise that fossil fuels were an unsustainable foundation for a prosperous future [15]. During this period, the fossil fuel economy became increasingly associated with the prospects of energy source depletion, energy security worries, and environmental pollution [20]. Motivated by these concerns, Bockris and Appleby turned to nuclear energy as the most promising alternative energy source, with hydrogen as a key energy vector. The only real alternative, according to Bockris and Appleby, was solar energy but that was still in its 'infancy' stage and was therefore not a competitor [15]. Their idea quickly gained support, especially from a self-styled 'hydrogen community' of researchers [21]. Between 1972 and 1977, there was a surge in scientific literature referring to large-scale deployment of hydrogen as an energy vector and using 'hydrogen economy', in their titles and abstracts. At the end of the 1970s, the excitement petered out, however [10]. Despite advocacy efforts by the hydrogen community, the energy revolution did not occur, while stagnation in nuclear energy and lack of broader societal support led to the hydrogen economy's decline.

In the 1970s, hydrogen was seen as a solution for clean and affordable global energy, closely tied to the vision of a nuclear society. We argue that this vision emerged and evolved as a techno-utopian narrative, rooted in utopian beliefs in a technological fix that combined the Atomic Age with hydrogen to provide affordable and accessible energy. Our findings are based on three recurring elements within the early hydrogen community: utopian terminology, fear of a dystopian future, and neglect of potential negative side effects.

The Second Wave started in the mid-1990s, when various non-academic actors actively explored the possibilities offered by a hydrogen economy. Especially, the promises made by automobile companies regarding pollution-free mobility on a commercial scale propelled the appeal of the hydrogen economy imaginary to new heights [22]. United States' President Clinton promoted hydrogen as a clean energy fuel for mobility [12] and Iceland expressed its ambition to become the first-ever hydrogen economy [23]. The Second Wave peaked in the early 2000s with very significant R&D activity in Europe, Japan and the US, where President George W. Bush touted it as the 'freedom fuel'. However, within a decade, the hydrogen economy became overly hyped, while delivery fell far short of expectations, leading to disappointment [12].

Today, we find ourselves in a Third Wave of renewed interest for hydrogen as a large-scale energy vector, fueled by concerns about climate change and the need for a fundamental energy transition. In the Third Wave of the hydrogen economy, hydrogen emerges as a key alternative for fossil fuel applications, integration of large-scale renewable energy sources and energy security. General policies, like those promoting large-scale energy transport, import and storage, emphasize hydrogen's diverse applications and potential collaboration across industries and sectors [2–8].

By understanding the origins of this ideology and its waxing and waning evolution since the First Wave, we can gain valuable insights into the current Third Wave of hydrogen interest and learn lessons that could enhance the success of today's hydrogen transition.

3. Methodology

3.1. Knowledge gaps

A knowledge gap exists in the current research on the hydrogen economy: most studies focus on the technical and economic potential of hydrogen as an energy vector and, in recent years, on the social aspects. The early developments of the hydrogen economy, corresponding societal ideals, and their link to the current hydrogen transition are often overlooked. It is important to realize, however, that the current vision for a hydrogen economy is not unique. Understanding the historical context is crucial, as it reveals resemblances, past challenges, successes, and misconceptions that can inform current strategies, help to avoid repeating mistakes, and shape more effective policies for the role of hydrogen in the energy transition. So far, the most significant historical publications about the early history of the hydrogen economy were written by prominent figures within the hydrogen community, specifically Veziroğlu [21,24,25] and Bockris [26,27], who provided their own experiences with the (early) development of the hydrogen economy ideal in the 1970s.

A few scholars have thoroughly examined the hydrogen economy through historical analysis. Notably, Martin Hultman, associate professor in science-, technology- and environmental studies at Chalmers University of Technology, has made significant contributions. He published on the development of the hydrogen economy ideal and its relation to the atomic energy ideal [28], the sociotechnological history of hydrogen and fuel cells in Sweden between 1978 and 2005 [13], and the expectations of fuel cells and the hydrogen economy between 1990 and 2005 [14]. His research focuses particularly on the turn of the millennium.

Another notable contribution is Marloes Dignum's doctoral thesis *The power of large technological visions — the promise of hydrogen energy (1970–2010)* [12] conducted at Eindhoven University of Technology. Dignum's study sheds light on the aspirations for the widespread adoption of hydrogen as a "large technological vision" primarily focusing on the period between 1990 and 2010. Thus, both Hultman and Dignum focused primarily on what we have called the Second Wave. Finally, a recent historical overview, including a quantitative analysis of the developments of the hydrogen economy between 1972 and 2020 is presented by Yap and McLellan [29].

Despite these contributions, a comprehensive historical analysis of the First Wave remains lacking, even though this is crucial to understand the emergence of the hydrogen economy's ideology, including its motivations, aspirations, and challenges. There is also limited exploration of the enduring elements of the hydrogen economy ideal. By combining our analysis of the hydrogen economy imaginary in the First Wave with insights into its further evolution during the Second Wave, this study aims to draw insights for the ongoing Third Wave and inform its integration prospects.

3.2. Research approach

This study employs a multi-method literature review, historical analysis, and sociotechnical imaginary analysis to uncover patterns and implications relevant to the hydrogen economy's evolution. We analyze historical developments prior to and during the First Wave and we highlight the connections between the Waves.

In the first part of this study, we explore developments leading towards the First Wave and analyze the First Wave from a historical perspective. This focus on the First Wave has several reasons: First, as the initial emergence of the concept, the First Wave is critical for understanding its foundational ideological roots. Second, while the Second Wave has already been extensively researched, there is limited exploration of the early development and motivations behind the First Wave. The still ongoing Third Wave lacks the historical distance necessary for analysis.

In the second part of this study, we provide a brief analysis of the Second Wave and a more extensive examination of the Third Wave. These approaches allow us to identify persistent themes and motivations that continue to shape the vision of the hydrogen economy, while also highlighting key differences between the Waves. This provides insights that bridge past and current challenges, offering historical context on the evolution of the vision for the hydrogen economy over 50 years.

3.2.1. Sociotechnical imaginary analysis of the First Wave

We analyze the emergence and evolution of the hydrogen economy's narrative and its community's motivations, using Jasanoff's concept of sociotechnical imaginaries [30]. Through this lens, we explore the actors, narratives, and motivations within the First Wave, with particular attention to how these visions aimed to address energy and societal challenges. This approach facilitates identifying recurring elements. Jasanoff defines sociotechnical imaginaries as: "[..] collectively held, institutionally stabilized, and publicly performed visions of desirable futures, animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology". ([30] p.6). Moreover, imaginaries often have a performative function: they are not only publicly shared, but they are shared with the aim of stimulating action in order to influence the realization of the imaginary. In other words, sociotechnical imaginaries are not just visions of the future; they also guide people's actions [31]. This framework allows us to examine how collective visions of desirable futures — animated by shared beliefs in the development of science and technology — shaped the ambitions and actions of the hydrogen community.

Additionally, we employ the concept of 'utopia' as elucidated by Vieira [32]. The concept of utopia has a rich history, dating back to the works of Plato and Thomas More, and has evolved since then. In the beginning of the 20th century, a group of prominent British and American intellectuals including H.G. Wells presented optimistic visions of the future, which were strongly technology-based. Their narratives have influenced postwar science fiction as well as non-fiction imaginings of the technological future [33].

Vieira provides a modern interpretation of utopia in a widely cited chapter in The Cambridge Companion to Utopian Literature [34], in which she discusses various interpretations of the utopian concept. Vieira argues that modern utopias, which became dominant after the Second World War, have departed from the traditional notion, which revolved around pursuing an 'impossible dream' of improving the world on a macro scale and criticizing the existing state of affairs. She writes, "[modern] utopia is now asserted as a process, and is incorporated in the daily construction of life in society [..]" and "[..] operating at a micro-level". ([32], p.22). However, Vieira argues that the modern utopia concept "[..] has by no means lost its critical perspective of the present [..]" ([32], p.22). She also identifies a dystopian streak within the modern interpretation. This dystopian aspect dominates images of the future in the second half of the 20th century, but with an important exception in late 1960s and 1970s when the traditional interpretation of utopia resurfaced. ([32], p.20).

To analyze the visions underpinning the hydrogen economy during the First Wave, we integrate Jasonoff's concept of the sociotechnical imaginary with Vieira's perspectives on utopia and dystopia. This integration forms the foundation for what we term the "techno-utopian narrative". This narrative positions the hydrogen economy as the cornerstone of a transformative energy future, addressing anticipated existential crises such as the energy crisis and environmental pollution. It frames hydrogen as a pathway to an "ultimate" energy economy — one that is clean, affordable, and accessible. During the 1970s, this vision was advocated by a specific group within the scientific community, seeking to promote and institutionalize their ideas.

To connect this analysis to the ongoing Third Wave, we assess how these imaginaries and narratives persist and evolved in contemporary discussions about the hydrogen economy over a 50-year span. This continuity provides insights into the long-term impact of foundational ideals on present-day energy transitions and specially the role of hydrogen and the hydrogen economy.

3.2.2. Multi-method literature review and historical contextual analysis

Given the existing knowledge gaps regarding the First Wave and the extensive research on the Second Wave, this study focuses on examining the evolution of the hydrogen economy during the 1970s. Specifically, we explore how ideas and developments from the earlier Waves remain relevant today, drawing lessons to enhance the success of the Third Wave.

The multi-method literature review involves several analyses, starting with a systematic literature review to examine the development of the different Waves and ensure comprehensive coverage of the early stages of the hydrogen economy. Through this systematic analysis, we were able to structure our exploration. Using the Google Ngram Viewer database — counting all digitized publications from the 1970s onward with 'hydrogen economy' in the title or abstract [10] — and the Web of Science database [11], we identified and defined three main Waves of surging interest in the hydrogen economy. This analysis helped establish a foundation for understanding the evolution of the hydrogen economy as an imaginary.

Additionally, a historical contextual analysis traces the developments that led to the emergence of the hydrogen economy ideal, situating these within broader historical and socioeconomic contexts. This approach provides an understanding of how early ideas influenced the evolution of the hydrogen economy imaginary.

Through the systematic literature review and historical review of extensive databases, we identified four key sources that influenced the early evolution of the hydrogen economy and its community, fostering the development of its collective vision. Following the identification of these key sources, we used the conceptual framework of sociotechnical utopias and utopian narratives to conduct a critical historical and discourse analysis of these sources to identify the foundational notions and expectations underlying the hydrogen economy ideal.

3.2.3. Reflection on the Second and Third Wave

In the second part of the paper, we conduct a discourse and stakeholder literature review to analyze the development of the hydrogen economy in the Second and Third Waves and to identify which actors are involved. We analyze what the hydrogen economy entails today. Through this analysis, we explore how stakeholder priorities and dominant narratives have shifted over time. For the Second Wave, the primary literature considered in this study includes the works of Dignum [12] and Hultman [13,14]. Given that this Wave extended beyond the scientific community, this literature is supplemented by industrial, governmental, and scientific publications, as well as 'gray' literature such as journalistic sources and news items published during this Wave. Given the Third Wave is ongoing, contemporary literature was utilized, encompassing scientific publications as well as industrial and governmental documents from the past decade, with particular emphasis on the last five years. This selection was guided by the need to reflect the most current and relevant sources, highlighting emerging trends and developments in the ongoing wave.

Additionally, we identify continuities and discontinuities in the evolution of the hydrogen economy ideal over three Waves. Finally, by situating these findings within the context of historical cycles of waxing and waning interest, we extract lessons to inform current momentum in the hydrogen economy and potentially guide current policy and decision-making in the hydrogen transition.

4. Historical context

To comprehend the advancements that led to the emergence of the hydrogen economy concept, we need to understand the historical context. In Fig. 3, we present an overview of main events up to and including the First Wave in a timeline. The subsequent sections will provide detailed explanations of these events and key milestones.

4.1. Advancements of hydrogen-related technologies and innovations

In the early 20th century, German chemist Fritz Haber devised a method for ammonia production utilizing hydrogen and nitrogen, which was subsequently scaled up to industrial levels by Carl Bosch,

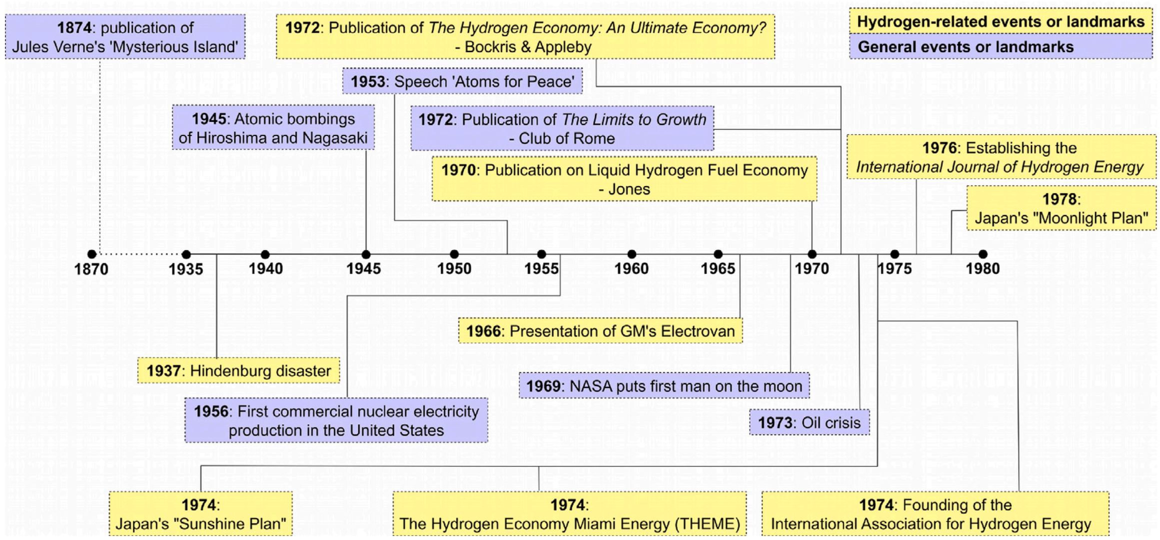

Fig. 3. Timeline of relevant events related to the emergence of the hydrogen economy and its growth in appeal in the scientific community in the 1970s.

revolutionizing the production of both explosives and artificial fertilizer. This Haber–Bosch process causes a huge increase in the demand for hydrogen [35].

Steam methane reforming (SMR) emerged as the predominant method for industrial hydrogen production in the 20th. SMR involves the reaction between natural gas and water to generate hydrogen and remains the most widely employed approach for hydrogen production today [35]. In addition to SMR, electrolysis — the splitting of water into oxygen and hydrogen — emerged as a prevalent hydrogen production method in the 20th century. Alkaline electrolysis (AEL) served as the predominant technology for electrolytic hydrogen production, alongside polymer electrolyte membrane electrolysis (PEMEL). The development of PEMEL was primarily motivated by the imperative need for oxygen generation in aerospace and submarine life support systems. It was not until the end of the 20th century that PEMEL was effectively employed for large-scale hydrogen production [36].

Hydrogen has also been employed for electricity generation. From the 1930s to the 1960s, various types of fuel cells, such as alkaline fuel cells, molten carbonate fuel cells, phosphoric acid-based fuel cells, solid oxide fuel cells, and PEM fuel cells, were investigated for their potential in electricity generation through hydrogen utilization [37]. Fuel cells especially garnered interest for their potential applications in rockets and spacecraft. They were considered to be efficient, reliable, safe, flexible, mature and generally a better option than alternative power systems [38]. NASA's choice for fuel cells caused a sharp increase in fuel cell research [38,39]. Next to hydrogen use for fuel cells, liquid hydrogen emerged as a preferred rocket propellant due to its superior efficiency in relation to volume [40]. Hydrogen technologies became a crucial element of the Space Age, garnering increased attention across other sectors as a result.

In 1966, General Motors, in collaboration with Union Carbide Corporation, introduced the Electrovan, the first fuel cell-powered electric vehicle. However, due to its high cost and complexity, the Electrovan remained primarily a research prototype rather than a commercially viable option [41]. Most of the aforementioned developments took place in the United States. However, on the other side of the Pacific, Japan became a front runner in the hydrogen-related technologies and innovations in the 1970s and 1980s. As a consequence of two significant governmental programs — the "Sunshine Plan" (initiated in 1974) and the "Moonlight Plan" (1978) — which were designed to advance renewable energy technologies, energy conservation, and environmental protection, fuel cell technologies were actively researched and developed [42]. In Japan, interest in hydrogen-related subjects has persisted to the present day [42–44].

4.2. Progress through technology: the atomic age

The notion that technological development contributes to societal progress has an extensive historical background. During the Enlightenment, science and technology were recognized as effective means to develop and improve society. Innovative technologies were regarded as "allies for building a better world" [45]. In the 1930s, the relationship with technological advancements strengthened in many Western countries. In response to the Great Depression, a technocratic movement emerged, aiming to address social and economic problems by replacing inefficient political systems and economic structures with technological rationality [46]. It reflected a widespread belief in the compatibility of societal progress and technology [47].

This form of thought persisted in subsequent decades. Johnston [48] argued that technocratic ideals were bolstered after the Second World War because of technological successes such as the Manhattan Project. This manifested in strong technocratic policies, including the Federal Aid Highway Act of 1956, facilitating the realization of the Interstate Highway System [49]. At the international level, one of the most influential technocratic policies was the Marshall Plan to reconstruct postwar Europe [50].

One of the most prominent advocates of the technocratic ideal was Alvin Weinberg, who was a nuclear physicist and member of the scientific advisory committee of the Eisenhower administration. Weinberg believed that innovative technologies and a solid engineering approach could solve any problem, even non-technical problems such as social, political, or cultural problems. He viewed 'technological fixes' as the most effective method for resolving such issues; much more so than political deliberation. Weinberg also played a crucial role in popularizing the concept of 'Big Science' [51].

One domain in which Big Science and the technological fix ideal converged was the nuclear energy program. In 1972, Weinberg wrote an article exploring the complex relationship between social institutions and the commitment to nuclear energy. In the post-war period, nuclear energy was envisioned as the primary alternative to fossil fuels. Initially associated with the atomic bombs that devastated Hiroshima and Nagasaki, the image of nuclear energy underwent a transformation in 1953 when U.S. President Eisenhower proposed a new vision for its utilization, transitioning from "Atoms for war" to "Atoms for peace" [52]. This paved the way for the Atoms for Peace program, through which the United States shared nuclear energy technology, training, and materials with other nations. The program had a dual purpose: to enhance the perception of nuclear energy's immense potential as a resource while also serving as a geopolitical message affirming the

United States' commitment to nuclear technologies [52] and portraying their increasing global influence.

The first operational nuclear power station, located at Shippingport, Pennsylvania, came online in 1956. After an initial period of slow development, the nuclear industry experienced rapid expansion, with a flush of permits for nuclear power plants in the second half of the 1960s that came online in the early 1970s [53]. This period established the United States as a frontrunner in nuclear energy, demonstrating not only the promise of affordable and clean energy on a large scale but also the steps taken towards widespread implementation [53]. This belief in the potential of nuclear energy triggered Bockris and Appleby [15] to develop their idea for the hydrogen economy with hydrogen as the energy vector in a nuclear energy-based society.

Hultman [28] points out that the potential of nuclear energy stimulated the idea that industrialized nations should redesign their energy systems. Nuclear energy was perceived as a catalyst for prosperity since it would "[..] create a society with vast quantities of energy for all kind of ends". (p. 227). Thus, nuclear energy was believed to have the potential to bring prosperity to society in general. The expected 'atomic society' or 'Atomic Age' was an imagined future with clear techno-utopian characteristics [28]. Geppert [54] notes that the Atomic Age, along with the 'Space Age', was "the epitome of modernity" (p.6), since both were deeply rooted in utopian and technocratic visions for progress and development [55]. The Atomic Age and the Space Age presented alternative and improved futures, based on technological developments that were often regarded as the ultimate step forward for humanity.

4.3. Energy systems in trouble

The optimistic expectation of unlimited cheap energy, whether based on fossil fuels or an imagined Atomic Age, did not last for several reasons. One of them concerned the availability of oil. Concerns regarding the depletion of fossil resources had been present since their initial widespread use [56]. The American geologist, geophysicist, and technocrat, Marion King Hubbert, working for Shell Oil, predicted in 1956 that oil production in the U.S. lower 48 states would peak in the early 1970s, which it did. This theory became the 'Hubbert Peak Oil Theory' or 'Hubbert Peak'. Hubbert proposed that production growth in any 'oil province' would inevitably come to a halt and decline would set in not long thereafter. On a global scale, Hubbert predicted that the peak would be reached in 2000 [57]. Although the calculations and predictions were accurate when confined to a specific type of oil resource and geography, new oil-producing regions (e.g. Alaska in the US) and resources (offshore, shale) were developed in subsequent decades. Due to these developments, oil production continued to increase. The concern did not go away, however.

In 1972, the Club of Rome [20] drew attention to the environmental consequences of human behavior, particularly the anticipated depletion of fossil resources. The report received enthusiastic support from environmentalists, but criticism from those who deemed it overly dramatic [58]. Within the scientific community, there were mixed reviews. Some researchers felt compelled to address the looming existential crisis while others expressed skepticism about the assumptions, research methods, and outcomes [59]. Nevertheless, the report contributed significantly to the mainstream recognition of environmentalism and resource depletion [60].

The Club of Rome report coincided with a growing awareness of the negative impacts of human industrial production, especially since Rachel Carson's influential book *Silent Spring* [61]. Carson's work aimed to highlight the environmental harm caused by society and she urged her readers to take action to prevent the further destruction of nature [62]. The book sparked academic debates on the social consequences of existing industrialized systems [63], including fossil-based energy systems.

In 1973, geopolitics provided yet another impetus for reevaluating the energy systems. During the first Oil Crisis, the export ban imposed by major oil-producing countries on the United States and other nations prompted a reassessment of energy production and supply [64,65]. The need to reduce dependency on a small number of countries further fueled discussions on transforming energy systems [65,66]. All these factors seemed to point to a need to change the existing fossil fuel-based energy system. However, as Mody [67] has argued, the oil industry was not a passive bystander: people related to oil companies were actively involved in many of the developments, including the development of alternative energy technologies. They tried to shape the debates, influence the direction of development of alternative technologies, and prepare the industry in case the energy system would indeed have to change.

All these developments took place in a context in which political institutions and economic structures were increasingly questioned: by the civil rights movement, second-wave feminists, anti-Vietnam War protesters, and by many-faced countercultural movements. Many intellectuals connected the problems of modern Western society to its economic structure. These movements resonated at universities, where students and researchers increasingly argued against military and corporate interests, and started debates about ethical, political and environmental consequences of science and technology. Collectively, these factors created an atmosphere during the 1970s that stimulated exploration of technological alternatives and fostered receptiveness to radical proposals [68]. The hydrogen economy concept by Bockris and Appleby was precisely such a radical proposal.

4.4. Summary of the historical context

To summarize, the emergence of the hydrogen economy concept is rooted in three primary historical developments: advancements in hydrogen-related technologies, the notion of technological solutions to societal challenges, and concerns surrounding contemporary energy systems. Firstly, during the 20th century, progress in hydrogen-related technologies sparked interest in hydrogen as an energy carrier. Secondly, the Atomic Age bolstered the concept of technological solutions to societal challenges, advocating for nuclear energy as a clean and abundant alternative to fossil fuels. Thirdly, apprehensions regarding the depletion of fossil resources, environmental issues, and geopolitical tensions surrounding oil production prompted a reassessment of energy systems and stimulated a search for alternatives. This shift in perspective paved the way for the consideration of large-scale hydrogen integration into energy systems, ultimately giving rise to concepts like the hydrogen economy as proposed by Bockris and Appleby [15].

5. Key papers of the First Wave and their reception

After the systematic and historical literature reviews, we narrow down the sources for further in-depth conceptual analysis. In the 1970s, discussions about the hydrogen economy were largely confined to the scientific community. We found that at the foundation of the emergence and evolution of the hydrogen economy was a small, but growing, scientific community that advocated hydrogen as an energy vector in their all-encompassing alternative to the existing fossil fuel-based energy system. At the core of this community were the 'Hydrogen Romantics' [21]. This collective collaborated with the shared goal of popularizing and realizing the transition to a hydrogen-based economy. We selected four scientific publications from people inside or near this group that we believe initiated the early development of the hydrogen economy imaginary and its associated community. Firstly, the paper *The Hydrogen Economy: An Ultimate Economy?* [15] in which the hydrogen economy as a concept was first introduced. Although a relatively short paper, it initiated discussions in the scientific community on what the hydrogen economy should become. Secondly, the article *Hydrogen Economy* [16], was the first elaborate study on the implementation of the hydrogen economy. This study materialized the abstract ideas by Bockris and Appleby in an outlook for potential implementation. Thirdly, the book *Hydrogen Economy: Proceedings of the Hydrogen Economy Miami Energy (THEME) Conference* [17], covered the publications and discussions from the first international hydrogen economy conference. It documented the first time the global hydrogen community came together and triggered a wider spread of the hydrogen economy ideal. Lastly, we consider the paper *Liquid Hydrogen as a Fuel for the Future* [18] a crucial source because of its focus on the conceptualization of the liquid hydrogen fuel economy and its similarities with the hydrogen economy concept. It shows that the emergence of the hydrogen economy was not a unique development.

5.1. Bockris and Appleby

In their 1972 paper, published in *The Environment This Month*, John Bockris and John Appleby introduced the concept of a 'hydrogen economy' [15]. Bockris, a chemistry professor at Flinders University in South Australia, stumbled upon a story about a Nazi engineer by the name Lawaceck who proposed using hydrogen as an energy vector. The engineer highlighted the cost-effectiveness of long-distance energy transmission through hydrogen pipelines compared to transmitting electricity through wires [26]. Bockris found this idea captivating, as he saw its potential as a clean and environmentally beneficial alternative to fossil fuels [26,27]. The notion of using hydrogen as an energy vector occupied his mind for several years, and, eventually, led him to collaborate with his former colleague, John Appleby from the University of Pennsylvania, to publish a joint paper on the subject. The paper titled *The Hydrogen Economy: An Ultimate Economy?* [15] was concise and did not delve into much detail. However, it ignited a scientific movement that firmly believed in the potential of hydrogen as the energy vector for an ultimate energy system and who actively began to promote their ideas after the group was formed at the first international hydrogen conference [17]. Following the initial publication on the hydrogen economy, Bockris continued to advocate for the hydrogen economy imaginary, while Appleby played a less prominent role in further promoting the idea.

At the outset of the paper, Bockris and Appleby explicitly state their vision: to make hydrogen the new predominant energy vector, with the ultimate goal of providing affordable and clean energy access to the entire global population, thereby facilitating the widespread improvement of living standards worldwide and prevent doomsday-like scenarios, such as those described by the Club of Rome [20]. They construed these scenarios as existential threats that could lead to the "break down" of societies within a few generations ([15], p.29). These assertions align closely with the dystopian undercurrents of the techno-utopian narrative, particularly as the authors proceeded to offer a way to avert these negative scenarios.

A key notion in their vision was that the future primary energy supply would rely on nuclear energy, both fission and fusion, with centralized production to capitalize on economies of scale. Bockris and Appleby believed that, by the year 2000, electricity would be generated from nuclear reactors at a production cost lower than conventional methods.

They envisioned nuclear reactors to be of considerable size and situated in remote regions: "The large reactors necessary to give cheap electricity will be on the oceans". ([15], p.31). Curiously, they do not provide an explanation for why nuclear reactors should be situated on the oceans, why they needed to be distant from populated areas, or how these factors would contribute to lower electricity generation costs. The only further elaboration provided was: "On an ocean location of a fusion reactor, raw material and electricity costs will be negligible". ([15], p.31). This implies that their primary concern was cost efficiency.

Bockris and Appleby regarded large-scale nuclear reactors as the only viable option for long-term, affordable, and clean energy. Although they briefly mentioned solar power as a potential alternative, they perceived the technology to be at a too low stage of development. In a subsequent publication [69], Bockris further explored the potential of solar power. He also thought that other sources such as "[..] gravitational, wind and geothermal power will never supply more than 15% of our energy needs". ([15] p.30).

Because of the remote location, the transport of energy to end-users posed a significant challenge. They dismissed electricity due to the high cost of transmitting it across long distances compared to other energy transportation methods. Consequently, they concluded that a standalone nuclear energy economy would not be feasible [15]. To address this issue, they proposed deploying hydrogen as a large-scale energy vector. Bockris and Appleby anticipated that converting electricity into hydrogen would be the most practical and cost-effective alternative for long-distance energy transport. Although they also considered other fuels, hydrogen was their preferred choice:

> Methanol, ammonia and hydrazine have been suggested, but hydrogen has advantages over each. Thus, methanol, if manufactured from limestone, would not only be costly, but would also lead to further CO_2 accumulation. The lower heating value of hydrogen per unit volume is offset by its lower viscosity (improved mass flow) characteristics, which give favorable estimated transmission costs per unit of energy. (p.31).

The promise of hydrogen for long-distance energy transport was foundational for their hydrogen economy vision. Bockris specified this notion further in his brief article, *A Hydrogen Economy* [15], emphasizing the cost-effectiveness of utilizing pipelines for hydrogen transmission, and again in the introduction of the book *Electrochemistry of Cleaner Environments* [70], where he writes: "Because of the low viscosity of hydrogen gas, it is cheaper (at distances above a few hundred miles) to push it in pipes". (p.19). This statement was based on the research conducted by Gregory, Ng, and Long [71].

5.2. Gregory

Even before the publication of Appleby's and Bockris' paper, Bockris and Derek Gregory connected through their academic network. Derek Gregory and his research group at the Institute of Gas Technology in Illinois became intrigued by the subject and conducted calculations to determine the cost-effectiveness of hydrogen transport. Their findings suggested that hydrogen transmission becomes more cost-effective than electricity transmission for distances exceeding two hundred miles [70]. This study by Gregory et al. [71] holds significance as it quantified Bockris and Appleby's abstract vision. Gregory further explored the potential of the hydrogen pipeline transmission network in his article *The Hydrogen Economy* in the Scientific American [16]. He asserts: "There is no reason [..] why hydrogen should not be distributed in the same way that natural gas is distributed today: by underground pipelines that reach most industries and more than 80% of the homes in this country" (p.14). Later he elaborates:

> The movement of fuel by pipeline is one of the cheapest methods of energy transmission; hydrogen pipelining would be no exception. A gas-delivery system is usually located underground and is therefore inconspicuous. It also occupies less land area than an electric-power line. Hydrogen can also be stored in huge quantities: by the very same techniques used for natural gas today (p.15).

To provide further insights into his notions, Gregory supplemented a schematic interpretation of the hydrogen supply chain, recreated as Fig. 4. According to his visualization, nuclear energy serves as the primary energy source, and an electrolysis plant is employed to convert electricity into hydrogen. Subsequently, the hydrogen is stored or transmitted through underground pipelines to other storage facilities or end-use applications, including local power stations, industrial fuel and reducing gas, synthetic chemicals and liquid fuels, as well as domestic

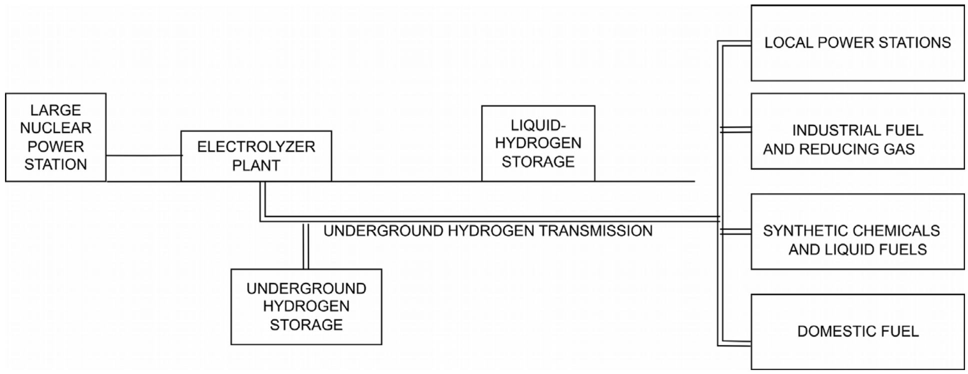

Fig. 4. Recreated schematic diagram of the hydrogen energy supply chain designed by Gregory ([16], p.5). The original subscription is as follows: "HYDROGEN ENERGY ECONOMY would operate with hydrogen as a synthetic secondary fuel produced from water in large nuclear or solar power stations (left). The hydrogen would be fed into a nationwide network of underground transmission lines (center), which would incorporate facilities for storing the energy, either in the form of hydrogen gas underground or in the form of liquid hydrogen above ground. The hydrogen would then be distributed as it is needed to energy consumers for use either as a direct heating fuel, as a raw material for various chemical processes or as a source of energy for the local generation of electricity (right)".

fuel. Gregory proposed that a portion of the hydrogen should be stored as liquid hydrogen due to its applicability as jet fuel and for gas-turbine engines. He states: "For this kind of use fuel storage and tankage as liquid hydrogen are practical". (p.20). However, he did not provide an explicit explanation for the practicality of this approach. Although he published several other articles on the subject, Gregory did not actively engage in the hydrogen community.

5.3. Veziroğlu, Hydrogen Romantics and the Association for Hydrogen Energy

In 1973, Cornell University hosted a series of conferences on the potential of the hydrogen economy. These were organized by Turhan Nejat Veziroğlu, a professor of mechanical engineering at Miami University. It was during one of these conferences that Bockris and Veziroğlu met and agreed to collaborate in promoting and advancing the hydrogen economy. Veziroğlu, who believed in the importance of collaboration between scientists and engineers to address significant societal challenges, saw the hydrogen economy as the most effective solution to fossil fuel depletion and environmental pollution [25].

Veziroğlu played a pivotal role in popularizing the hydrogen economy imaginary, dedicating his career to its advocacy after 1973. He played a major role in organizing the 1974 THEME conference, which attracted 700 participants from around the world and led to the organization of several other conferences. The THEME conference brought together a group of like-minded individuals, which initiated the hydrogen community who later referred to themselves as 'Hydrogen Romantics', with Bockris and Veziroğlu at its core. This informal international group consisted of professors, engineers, and consultants, predominantly from chemical and mechanical engineering backgrounds, who shared a common vision for the hydrogen economy [21].

In 1974, the International Association for Hydrogen Energy was established, with the goal of promoting effective communication and interaction among the various components of the hydrogen economy. Veziroğlu became president, and most members of the Hydrogen Romantic joined the board. In 1976, as the scientific community involved in the hydrogen economy expanded, the International Journal of Hydrogen Energy was established, with Veziroğlu as its first editor [72].

5.4. Lawrence Jones and the liquid hydrogen fuel economy

The final key figure discussed in this section is Lawrence Jones, a physics professor at the University of Michigan. Jones was not an early member of the Hydrogen Romantics, but he did join the advisory board of the International Association for Hydrogen Energy in 1976. Although Jones introduced his ideas prior to the publication of Bockris and Appleby's paper on the hydrogen economy, we discuss him last to emphasize the broader impact that Bockris, Appleby, and later Veziroğlu had in shaping the narrative. This also allows us to contextualize Jones' contributions within the larger, more influential movement and highlight how his ideas, while important, remained primarily focused on hydrogen as a transportation fuel and were less widely recognized at the time.

In 1971, Jones introduced the 'Liquid Hydrogen Fuel Economy' concept, proposing: "[..] liquid hydrogen as an ultimate replacement for fossil hydrocarbon fuels in vehicular and aircraft transport [..]" ([18], p.1). Jones believed that the significant drop in the price of liquid hydrogen during the 1960s made it technically and economically feasible, and perhaps even "inevitable" ([18], p.1) as a substitute for oil. He justified this viewpoint by emphasizing the finite nature of fossil resources and the eventual crisis resulting from their consumption [18].

Jones' concept shares similarities with Bockris' and Appleby's hydrogen economy concept. Both concepts address concerns regarding the depletion of fossil fuels and anticipate an expanded role for hydrogen as a substitution. He also contributed to the first hydrogen economy conference in 1974 [17]. However, there are also some notable differences. While Jones focused on liquid hydrogen as a transportation fuel, Bockris and Appleby considered various forms of hydrogen and explored applications beyond the transportation sector. Additionally, Jones advocated for steam reforming with CO_2 removal through solvents as the most cost-effective method for producing liquid hydrogen. He believed this approach to be even more economical than hydrogen produced through nuclear power, basing his claims on two studies [73,74].

Jones identified four possibilities for non-fossil fuel alternatives for transportation: electrochemical storage battery, fuel cells, internal-combustion engines, and external-combustion engines. In contrast, Bockris and Appleby focused primarily on non-Carnot-limited devices. The liquid hydrogen fuel economy and the hydrogen economy differed substantially. However, Jones' concept illustrates that Bockris and Appleby's idea was not entirely novel or unique. The potential of hydrogen as a large-scale energy vector had already been explored.

We argue that Bockris and Appleby, later advanced by Veziroğlu, initiated the hydrogen economy movement, not Jones, for two main reasons. First, Jones viewed hydrogen primarily as a solution for transportation fuels, whereas Bockris and Appleby envisioned it as a comprehensive energy carrier. Second, Bockris, with Veziroğlu's assistance, actively promoted their hydrogen vision to the scientific community through conferences and public events, thereby garnering significant support.

6. Hydrogen economy as a techno-utopian narrative

The hydrogen economy ideal has many characteristics of a sociotechnical imaginary. In this vision, hydrogen as an energy carrier for nuclear energy was the logical technological advancement towards an 'ultimate' economy in which clean, affordable, and accessible energy supply for many different applications would be available. Specifically, this vision implied that scientific and technological advancements would establish a hydrogen economy capable of permanently resolving existential challenges such as the energy crisis and environmental pollution. We have termed this sociotechnical imaginary the 'techno-utopian narrative', as the narrative reflects a transformative shift in both social and technological dimensions, aligning with the sociotechnical imaginary framework. For the hydrogen community in the 1970s, nuclear energy was the foundation but hydrogen was the necessary next step in exploiting this inexhaustible energy source. The ambitions embodied their collectively held vision of a desirable future, driven by shared understandings of a more sustainable and technologically advanced society achievable through the development and utilization of hydrogen as the main energy carrier. It was rooted in post-Second World War socio-political developments, especially prevailing perspectives on science and technology, which are exemplified by the close connection between the emergence of the hydrogen economy imaginary and the expectations surrounding nuclear energy during the 'Atomic Age' [28].

In our analysis, we identify several characteristics of both traditional and modern utopian narratives, based on Vieira's work [32]. The main utopian elements are: a hopeful outlook towards a more favorable future, a proactive search for alternatives within the prevailing energy system, an inherent confidence in science and technology, and the widespread use of optimistic terminologies. In the 1960s and 1970s, this was catalyzed and carried out by activists and environmentalists such as ecologists, feminists, and New Left thinkers. It did not center around an unattainable perfect world but rather focused on the pursuit of a better future. Termed as 'critical utopia', this approach was seen as more realistic. It represented a form of activism based on the belief in actively transforming society [32]. Characteristics of techno-dystopian narratives are visions of current misuse of science and technology, leading to an undesirable future and even existential threats to human civilization [32]. Finally, an important characteristic of utopian narratives is the downplaying or omitting of information regarding potential drawbacks and negative side effects of the key technology of the narrative.

We identify these elements in the key publications of the early hydrogen economy advocates, especially focusing on the language used in those publications. Techno-utopian characteristics can be recognized by the use of terminology such as 'positive', 'infinite', 'necessary', 'inevitable', 'ultimate', and 'permanent' relating to a key technology. Additionally, we pay attention to the omission of information, such as neglect of negative side effects. For this period, we focus on both optimistic expectations of hydrogen's potential as a global energy vector (traditional utopia interpretation) and the increasing apprehension of the impending challenges associated with the existing fossil energy economy (dystopian images as part of the modern utopia interpretation).

6.1. Traditional utopian terminology

In the article by Bockris and Appleby, utopian terminology is clearly present. They use many superlatives to depict the hydrogen economy, referring to it as the potential 'ultimate economy'. To them, this represents a final, enduring, permanent and, above all, improved future economy. This sentiment is also evident in the concluding section of their article [15]:

> No pollution would be involved; it would provide fresh water, and simplified, non-polluting ways to carry out many chemical and metallurgical tasks. Energy growth will be limited only by thermal pollution in population centers. [..] Provided that these conditions can be achieved, the Hydrogen Economy may be expected to last as long as the solar system endures. (p.35).

Similarly, Jones [18], preceding Bockris and Appleby, referred to liquid hydrogen as the "ultimate replacement for hydrocarbon fuels" (p.367) and asserted that liquid hydrogen was "desirable and perhaps even inevitable". (p.367). In the work by Veziroğlu, we also observe the presence of traditional utopian terminology to promote alternative and better futures. He repeatedly portrayed the hydrogen economy as an inevitable development. This is exemplified in his review of the first hydrogen economy conference in 1974 [21]: "It was agreed that the Hydrogen Energy System [..] was an idea whose time had come. It was the permanent solution to the depletion of conventional fuels. It was the permanent solution to the global environmental problems. (p.1143)". The choice of the word 'permanent' is noteworthy, emphasizing that Veziroğlu considered the hydrogen economy to be a lasting solution rather than a temporary fix.

Traditional utopian terminology is also evident among other members of the hydrogen community. Dell and Bridger [75] regarded hydrogen as an 'ultimate fuel' and Gregory [76] also considered hydrogen as the "[..] ultimate replacement of our conventional fossil-fuel economy [..]" (p.239). Harrenstien [17] adopted a deterministic perspective, viewing hydrogen: "[..] as the fuel of the post-fossil-fuel era" ([17], p.x). Within the community, it was perceived as the permanent and ultimate alternative to the existing fossil fuel economy. Their work also showed great confidence in the benefits of scientific and technological progress, another recurring element within the techno-utopian narrative. Gregory stated in *The Hydrogen Economy* [16] that the solution to the world energy crisis depends primarily on two aspects: "[..] developing alternative sources of energy [..]" (p.13) and "[..] devising new methods of energy conversion". (p.13). Thus, technology is an essential tool to improve society.

6.2. Dystopian spirit

In the foreword of *Hydrogen Economy: Proceedings of the Hydrogen Economy Miami Energy (THEME) Conference* [17], Harrenstien, chair of the event, writes: "Many of us, scientists and engineers, believe that replacing fossil fuels with the inexhaustible and clean synthetic fuel, hydrogen (produced from non-fossil primary sources of energy) will answer the [..] problems". (p.xii). With these problems he referred to the: "[..] depletion of fossil fuels, demand for more energy, and the pollution of our environment". (p.xii). This reflects a dystopian spirit since the existing technology is seen as the fundamental cause of the problems, and transitioning to improved technology is seen as a pathway to an alternative and improved future.

The challenges of the fossil fuel economy, as delineated by Meadows et al. [20], was posed as an existential threat. It is clear that Bockris and Appleby believed that the so-called 'doomsday' scenario could be prevented. *The Hydrogen Economy: An Ultimate Economy?* [15] clearly displays characteristics of a techno-utopian narrative, including dystopian images for the future: Bockris and Appleby presented a distressful scenario, while introducing an alternative that heavily relied on a technocratic approach.

Dystopian images can also be found in the works of other members of the hydrogen community. Gregory [16] refers to a 'world energy crisis' and a world that would be "[..] suffering unacceptable levels of pollution". (p.13) due to the consumption of fossil fuels. Veziroğlu, in the preface of the book on THEME [17], states that there are "[..] three important problems facing the world: depletion of fossil fuels, demand for more energy, and the pollution of our environment". (p.xi). Additionally, in the book edited by Bockris [70], several chapters (indirectly) reference the existential threat and the associated problems. The hydrogen economy was presented as a realistic alternative to prevent these dystopian future scenarios.

6.3. Neglecting negative side-effects

Finally, in accordance with traditional utopian spirit, the negative effects of revolutionizing the energy system were downplayed or ignored. This crucial aspect of the techno-utopian narrative is evident in the key works of the First Wave. For example, Bockris and Appleby [15] assign a key role to nuclear energy, but they do not discuss any possible drawbacks of either fusion or fission. Hultman [28] also emphasized that there was little room for negativity: “The emphasis on one side — the positive side — of the scientific change originating at this time downplayed all the fear and negative consequences also evoked by the innovative technology”. (p.227). This can be explained by the necessity or need, as Hultman [28] describes it, for “[..] harmony [..] according to which economic, ecological, and social issues can be managed using modernistic knowledge and models knowledge and models from modernity, is by now also being formulated as a utopia proper”. (p.227). This one-sided view dominated rational thoughts concerning both the atomic society and a hydrogen economy.

Some scientists criticized the hydrogen economy, mostly focusing on technical issues related to storage, safety, efficiency, and cost, but these problems were mostly considered solvable [75,77]. For instance, Williams [78] highlighted various problems and obstacles, such as explosion risks, the imperceptibility of hydrogen to the human senses, and the economic challenges that would need to be addressed. Nevertheless, like many others, Williams remained confident that the issues would all be resolved or mitigated, stating: “A combination of technical development and the expected adjustment in relative energy prices can justify the economics, and proper practices and design can ensure safety” (p.21). Jones [18] went as far as to say that hydrogen was, in many ways, “safer than gasoline” (p.370) and that hydrogen explosions will be “very rare in practice” (p.370). In pursuit of the ideal future, there was little room for nuanced discussions [28].

To summarize, we posit that the First Wave of the hydrogen economy imaginary emerged as a response to a growing awareness that the current fossil-based economy was unsustainable due to the risk of energy source depletion and, to lesser extent, energy security and environmental pollution. For both cultural and (geo)political reasons, the scientific community was receptive to radical alternative proposals. The hydrogen economy could offer a technocratic future, presented in both utopian and dystopian narratives.

6.4. Decline of the First Wave

The hydrogen economy imaginary peaked in the 1970s, but interest seemed to die down quickly after that. Although many conferences were held and most of the Hydrogen Romantics remained active [21], they failed to gain wider support for their techno-utopian vision. One possible reason for the decline was the fact that the oil crises were overcome [79]. Fossil fuels were less scarce since new oil reserves were discovered or existing reserves were larger than expected [80]. Another reason may be changing popular views on nuclear energy regarding safety and nuclear waste. After all, nuclear energy was still a key element of the vision for the hydrogen economy. The deployment of nuclear energy declined from the second half of the 1970s [81], and the anti-nuclear movement grew [82]. Finally, political changes in the United States and Britain meant there was less support for long-term alternative energy strategies [67]. As a result, the hype ended. Interest in alternative energies dwindled; in the 1980s, fossil fuels were more entrenched than ever. The hydrogen economy, like the Atomic Age, remained an unrealized ideal.

7. The Second and Third waves

In this section, we will discuss the Second and Third Wave of interest in the hydrogen economy. Some observations are made regarding the core similarities and differences between the Waves to assess whether the Third Wave has the potential to become a successful hydrogen transition.

7.1. The Second Wave

The Second Wave represents a crucial phase in the evolution of the vision for a hydrogen economy. From the mid-1990s to the late-2000s, there was a surge of interest in hydrogen as a large-scale energy vector [12]. This period was characterized by a focus on the implementation of the hydrogen economy in the near- and midterm, especially in mobility. During this Wave the hydrogen economy ideal was supported more widely and represented a step-up towards the actual realization of a hydrogen economy, as compared to the purely abstract and theoretical discussions by a small group of Hydrogen Romantics during the First Wave.

The actors during the Second Wave were a more varied group than during the First. They included national governments, the automobile industry, the scientific community [12], and the media [14]. They also came from a wider range of countries. Governmental support played a crucial role, with high-profile supporters such as former US President Bush, who described hydrogen as the ‘Freedom Fuel’ [83]. Additionally, the California Zero Emission Vehicle (ZEV) mandate incentivized the global automobile industry to explore hydrogen as an alternative clean fuel [84]. In Europe, the public–private partnership Fuel Cells and Hydrogen Joint Undertaking (FCH JU) had the ambition to enable the market introduction of fuel cell and hydrogen technologies [85]. The Japanese government implemented the Millennium Project to foster the development of fuel cell vehicles and residential fuel cells [86]. The scientific community also increasingly focused on hydrogen deployment research, for example, by highlighting potential benefits of highly efficient energy conversion with fuel cells over combustion engines [87,88].

Media amplification fueled public enthusiasm by presenting hydrogen as a clean and environmentally friendly solution. The connection between hydrogen and water, a symbol of cleanliness and sustainability, contributed to its positive portrayal in the media [14]. Overall, these factors created a strong momentum. Hydrogen expectations were more widely embraced in society than during the First Wave [12].

Just as in the First Wave, there were clear techno-utopian elements within the hydrogen economy imaginary during the Second Wave, particularly in the United States. Fuel cell technology was seen as a key technology [12] and considered a *sine qua non* for a low-carbon future [13]. The U.S. Department of Energy [89] referred to hydrogen as the “future energy source”, while The New York Times [90] described it as “an abundant environmentally clean source of energy”. The automobile industry promoted Hydrogen Fuel cell vehicles as *the* car of the future. The exhaust of fuel cells was indeed clean, but this representation overlooked the fact that hydrogen production at that moment still relied on fossil fuels [12]. It thus portrayed a rather more optimistic image of the hydrogen economy than was warranted by contemporary reality.

Despite initial optimism, practical and technical challenges emerged which prevented widespread adoption in the first two decades of the 21st century [12]. The appeal of hydrogen-fueled cars for consumers was limited by delays in the development of the fuel cell vehicles, infrastructure hurdles including the lack of hydrogen fueling stations, and the rise of alternatives such as the hybrid-electric vehicle. Cost barriers, reliance on fossil fuels for hydrogen production, and corresponding environmental concerns also hindered progress of the hydrogen economy in other areas [22,91]. Eventually, public support waned, leading to the end of the Second Wave in the second half of the 2000s.

7.2. The Third Wave of hydrogen enthusiasm

Today, companies, policymakers, and the scientific community once again embrace the potential of hydrogen as a large-scale energy vector [3,5]. The amount of (inter)national hydrogen strategies has almost tripled since 2021, and at least 60 have been published [92]. The current resurgence of interest is driven by a multitude of factors, including growing concerns about climate change, the quest for energy security, and the recognition of hydrogen as a versatile energy vector [5–8]. In this Wave, hydrogen is envisioned not only as a clean alternative to fossil fuels but also as a facilitator of the integration of large-scale renewable energy sources into a sustainable energy system [93–96]. It is envisioned that hydrogen will play a key role in the storage and transport of renewable energy. As countries strive to reduce greenhouse gas emissions and transition towards more sustainable energy systems, hydrogen emerges as a promising solution due to its potential to decarbonize various sectors, including transportation and industry [97–100]. Hydrogen is viewed as one component within a diverse energy mix including electricity, biomass, and hydrogen derivatives [101,102]. Moreover, the Third Wave emphasizes the importance of energy security, particularly in the context of geopolitical tensions and uncertainties surrounding traditional energy sources [103,104]. By diversifying energy sources and reducing dependence, hydrogen offers a pathway towards greater energy independence and resilience [104].

Overall, compared to the first two Waves, the Third Wave reflects a development from idealized visions towards early steps for implementation, acknowledging the complexities of integrating hydrogen into real-world energy landscapes.

7.2.1. Continuities and discontinuities in the 50-year evolution of the hydrogen economy

Over the 50-year span between the initiation of the First Wave and the current state of the Third Wave, the hydrogen economy has undergone significant evolution. We identify several key parallels and differences between the different Waves.

Existential threat. During the First Wave, the predominant motivation for the hydrogen economy was linked to the fear of the depletion of fossil resources as an existential threat [20]. A similar sense of urgency to take action is evident during the current Wave. Comparable to the hydrogen economy imaginary of the 1970s, hydrogen is again perceived to play a pivotal role in mitigating existential threats [5–8]. But while the finite nature of fossil resources remains a concern, the current focus is on addressing urgent climate risks and promoting sustainable energy solutions. In both cases, hydrogen is framed as a key solution to a global crisis affecting humanity.

Energy security. A parallel can be recognized in the pursuit for energy security, with an energy system that is not reliant on a few singular nations or entities. The oil crisis of 1973 made many countries realize the need for an energy system that was less dependent on a few countries (especially Middle Eastern ones) [64–66]. The last few years, the hydrogen economy imaginary also obtained more traction because of geopolitical developments. The energy crisis of 2022, resulting from Russia's invasion in Ukraine, served as a wake-up call for many countries to focus more on energy security. Various initiatives were explored to minimize the dependence on fossil fuels imported from Russia [105,106]. Notably, the REPowerEU scheme was developed to gradually eliminate European dependence on fossil fuel imports from Russia. A pivotal element involved the acceleration of the plans for the production and import of renewable hydrogen to replace conventional fossil fuels in hard-to-decarbonize sectors [107].

Hydrogen as energy vector. As highlighted by Bockris and Appleby [15] and elaborated by Gregory [16], the consideration of hydrogen over electricity during the First Wave was related to its potential for cost-effective large-scale energy transport. Today, the ambition persists to utilize hydrogen as a replacement for fossil fuels and a carrier for transporting large amounts of energy. In the IRENA report [108], a global hydrogen trade is envisioned for 2050, with the Global South as the primary exporters and the Global North as the main importers, driven by high energy demand. Instead of nuclear energy, however, the primary sources today include solar and wind energy, although biomass [109], nuclear energy [110,111], and fossil-based sources with carbon capture [112,113] are also under consideration for low-carbon hydrogen production. In the study by Incer-Valverde et al. [114], ten different 'colors' for hydrogen are identified each referring to different sources or methods for the production of hydrogen. This indicates that the vision of hydrogen as an essential energy vector persists.

During the First Wave, the hydrogen community viewed hydrogen as *the* most crucial element of an ultimate economy. However, today, it is recognized as part of a more diverse array of energy sources and carriers. The IEA published an energy roadmap for 2050 in the *World Energy Outlook 2023*. Here, the final total energy consumption of hydrogen varies from zero to 8.5 percent depending on the selected scenario [115]. Across all scenarios in the report, electricity consistently constitutes a significantly higher share of the final energy consumption.

Hydrogen supply chain and applications. The significance of developing extensive hydrogen supply chains is a key aspect of the hydrogen economy visions across all three Waves.

The primary technology considered for large-scale hydrogen production remains electrolysis. Additionally, the methods to transport hydrogen are envisioned mostly the same as during the First Wave [16]. With the unevenly distributed and location-constrained renewable energy sources that are often far away from energy demand location [116,117], hydrogen enables the transport of vast amounts of energy through pipelines. In Europe, the implementation of a large-scale hydrogen transport network is actively being discussed. The member states of the European Union have propagated an extensive plan to create a European pipeline network named European Hydrogen Backbone for hydrogen transmission reaching the outer parts of Europe by 2040. For this project, many new pipelines need to be constructed, or existing natural gas pipelines may be repurposed [118].

However, the evolution of hydrogen supply chains, including considerations of hydrogen carriers and end-use applications, reflects changing technological and logistical priorities [119–122]. Given the energy-intensive nature of hydrogen production [123,124], diverse perspectives exist on the optimal applications. Liebreich Associates has devised a 'hydrogen ladder', outlining a hierarchy of hydrogen applications. Notably, hydrogen's use to produce fertilizer holds a top-tier priority due to the limited alternatives, rendering hydrogen use in this context 'unavoidable'. Conversely, and in contrast to the Second Wave, hydrogen-fueled personal vehicles rank low in the hierarchy, given the availability of electricity as a much more cost-competitive alternative [125]. In 2023, global sales of hydrogen-fueled vehicles experienced a decline of approximately 30 percent, dropping from 20,700 in 2022 to 14,415 in 2023 [126]. Meanwhile, sales of electric and hybrid vehicles surged from 15.35 million to 17.07 million globally, an increase of over 10 percent, primarily attributed to the growing popularity of electric vehicles [127]. The competitiveness of electric vehicles is acknowledged by critics who argue that hydrogen as a fuel may not be economical and energy-efficient enough for personal vehicles [128,129].

Support for the hydrogen economy. The deployment of hydrogen as an energy vector has obtained much more attention from policymakers, politicians, and commercial entities during the Second and Third Waves than during the First. During the First Wave, the supporters mainly included parts of the scientific community, with most of their activities in the United States. Today, the hydrogen economy enjoys significant endorsement from diverse sectors and countries, reflecting not only technological optimism but also political and economic interests. Governments, industry stakeholders, and environmental groups are increasingly aligning their efforts around hydrogen, motivated by a blend of energy security concerns, climate goals, and economic opportunity. Under the REPowerEU scheme, the EU aims to both produce and import 10 Mt of renewable hydrogen by 2030 [107], while current production and imports remain negligible. Additionally, the United States have devised pathways for clean hydrogen [130] and Japan is consistently advancing its plans for a hydrogen economy [42–44].

Studies by Hultman [13,14,28] and Dignum [12] have demonstrated a similar increase in policy and planning-related activities that occurred during the Second Wave. But the level is higher in the Third Wave. Taken together, we see an evolution of the hydrogen economy from a more abstract future ideal in the 1970s to progressively a more pragmatic orientation in the Second and Third Wave.

Influential actors. Similar to the Second Wave, established stakeholders within the fossil energy sector are deeply involved in creating a favorable narrative for hydrogen as an energy vector. Studies by Lowes et al. [131], Szabo [132], and Vezzoni [133] illustrate how, in particular, the natural gas industry has a strategic interest in emphasizing the advantages of clean gas over electricity by utilizing existing (natural) gas infrastructure. These incumbents also emphasize the role that 'blue' hydrogen — hydrogen from natural gas with carbon capture and storage — could play in the transition towards a fully renewable energy system. Szabo [132] dubbed the continued reliance on fossil fuels a "Fossil Capitalism's Lock-in".

Lowest et al. Szabo, and Vezzoni [131–133] argue that these efforts of the natural gas industry have had significant effect on policy making. Lowes et al. [131] present an example, showing that a coalition of large fossil fuels actors, presenting themselves as 'Decarbonized Gas Alliance', are actively framing 'green gas' — hydrogen and biomethane — as a low-cost solution to decarbonize the UK's gas grid, enabling reusing existing infrastructures and maintaining consumer habits. Motivated by the threats of upcoming electrification, this 'green gas storyline', as Lowest et al. [131] call it, is used by the gas and oil industries to influence the political debate to serve their interests. It aligns with their efforts to remain relevant and profitable in a shifting energy landscape. However, this may be problematic because it is uncertain if the transition to green gas is cheaper or leads to lower emissions, while electrification is proven to reduce emissions immediately [131].

Szabo [132] is concerned that lobbying within the hydrogen transition, backed by substantial financial resources, could maintain the dependence on fossil fuels. Investments in blue hydrogen may undermine the competitiveness of renewable hydrogen [133] and divert focus from sustainable alternatives [131] or energy reduction efforts [133]. While it is good to be vigilant about the pressure of calculated strategies by entrenched interest groups to preserve their economic and political influence [132], and to be alert to the potential disincentives for green hydrogen resulting from a focus on blue hydrogen, there is actually little evidence that this is in any way happening (see e.g. the analysis of stakeholder perspectives in Jesse et al. [134]).

7.3. Has the techno-utopian narrative persisted?

We have identified a techno-utopian narrative in the First Wave, including utopian terminology, fear for dystopian futures and ignoring negative side effects of the hydrogen economy. The First Wave can be characterized as highly idealistic, but its ambitions were never reached.

Dignum identified the hydrogen economy during the Second Wave as a Large Technological Vision (LTV). She describes LTVs as: "LTVs centralize (a specific) technology and attribute great transformative power to that technology including large (positive) societal consequences once a novel promising technology is widely adopted and has reached a prominent position". ([12], p.11). This vision shares many similarities with the techno-utopian narrative, though it is not entirely the same, as it includes aspects of adoption and practical implementation. Still, like for the First Wave, most of the goals for the hydrogen economy remain unachieved in the Second Wave.

In the Third Wave, there remains faith in scientific and technological progress of hydrogen as a large-scale energy vector [5,135,136]. Hydrogen is often presented as playing a "key role" [3] or as an "important fuel" [137] in the sustainable energy transition, alongside other energy sources and carriers. Despite growing optimism, the Third Wave acknowledges significant barriers to hydrogen's widespread adoption. These include high production costs, the need for substantial infrastructure development, and challenges related to hydrogen storage and transportation [2,138–140], but also social concerns such as fear of high societal cost and safety risks [141]. These challenges reflect the complexities of transitioning from idealized visions to practical, large-scale implementation.

Still, reports by consultancies such as McKinsey [142] and DNV [143] underscore the perceived importance of sharp increases in (renewable) hydrogen in the upcoming decades, marking it as "essential" [143]. Similar to earlier Waves, the hydrogen economy in the Third Wave is approached as a technological solution to overcome society-wide problems. The focus remains on developing new, cost-effective technologies to provide clean energy globally, prioritizing technological advancements over behavioral changes such as reducing energy consumption. In the Third Wave, the hydrogen economy is positioned as a solution to mitigate the effects of a perceived dystopian future caused by climate change. Unlike previous Waves, however, the impacts of this dystopian concern are tangible daily already, highlighting the urgency for solutions. Still, hydrogen is seen more as one of the pragmatic tools to prevent further escalation of the problem rather than a vision of the 'ultimate' and 'lasting' solution. Hydrogen is increasingly viewed as a key component in the broader energy transition, complementing other renewable energy technologies. While hydrogen's potential for decarbonizing hard-to-abate sectors is clear, its role must be seen alongside efforts to electrify, enhance energy storage capabilities, and reduce overall energy consumption. Also, unlike in previous Waves, there is more recognition of the potential negative side-effects of the hydrogen economy in the Third Wave. The presence of hurdles and challenges, including costs, technological development, and scaling, is acknowledged.

In summary, the hydrogen economy is no longer presented as a techno-utopian narrative and a single solution for preventing doomsday scenarios but rather as part of a broader solution to pressing issues, including (seasonal) energy intermittency, large-scale renewable energy transport, and climate change mitigation [2–5,144]. However, the Third Wave has yet to mature into an effective hydrogen economy, and a successful role for hydrogen in the energy transition is not guaranteed.

7.4. Lessons from past Waves

Based on our analysis of the three Waves, we can derive four lessons to bolster the successful outcome of the Third Wave.

First, while nuclear energy was central to the First Wave's hydrogen vision because of its perceived potential to provide affordable energy, the Third Wave advocates for a diverse energy portfolio, incorporating nuclear energy, solar energy, wind energy, and other (renewable) sources. The challenge lies in ensuring these technologies can be scaled at a low cost, enabling the large-scale hydrogen production needed for a global hydrogen economy. The synergy between low-cost, available, and accessible energy sources and hydrogen production will be a key factor in the economic viability of hydrogen solutions.

Second, similar to the First Wave, hydrogen is expected to be transmitted over long distances. This highlights the need to establish an extensive and efficient infrastructure to bolster the efficiency and adaptability of the hydrogen economy. Within the Third Wave, plans are made to develop this, which indicates that the hydrogen economy has matured further than its preceding Waves. Still, much needs to be done before it can operate on the necessary scale. To realize hydrogen's full potential, governments and private stakeholders must collaborate on building and repurposing the pipelines and storage while addressing regulatory and societal challenges related to land use, safety, and investments.

Third, ambitious goals were central to both the First and Second Waves, but unrealistic expectations led to disillusionment when these targets were not met. During the First Wave, hydrogen was presented as a panacea for various challenges and contributed to the hype surrounding the hydrogen economy. However, the utopian beliefs lead to disappointment. During the Second Wave, hydrogen was specifically mentioned as a clean fuel for vehicles. This, again, did not meet the expectations: Automobile companies published statements that hydrogen vehicles would soon become commercially viable, but when this milestone was repeatedly not realized, this resulted in widespread societal disenchantment with the feasibility of hydrogen as a fuel in general [145]. Today, existing plans are being delayed or canceled [146–148] showing that some plans are overly ambitious or unwanted for other reasons. This could lead to a decline in confidence in the viability of a hydrogen economy. The Third Wave must focus on setting achievable, incremental milestones and fostering public trust by ensuring that hydrogen technologies are progressively integrated into real-world applications. Avoiding overly ambitious claims will be key to maintaining confidence and long-term momentum.

In past Waves, hydrogen was viewed as a ‘silver bullet’ capable of solving a range of energy challenges, from clean transport to industrial decarbonization. It is crucial not to be overly optimistic about the quantity of (clean) hydrogen that will be accessible. Past disillusionments have shown the importance of viewing hydrogen as part of a broader set of solutions. Its role should be prioritized in sectors where alternatives are scarce and its benefits are most evident. As Fressoz [149] argues in *More and More and More: An All-Consuming History of Energy*, energy transitions are characterized by additions to existing energy systems and gradual transformations rather than abrupt breaks or rapid replacements.

Fourth and last, the First Wave was primarily driven by a segment of the scientific community and did not advance the hydrogen economy beyond the conceptual phase. During the Second Wave, multiple actors were involved, but they did not realize their hydrogen economy ambitions. Still, the Second Wave was more mature than the First Wave, with a focus on near- and midterm implementation of the hydrogen economy.

The Third Wave has broader support, but decisive action is needed for an effective hydrogen transition. There is an ongoing debate on how to develop (large-scale) hydrogen markets. For instance, a significant challenge arises from the ambiguity surrounding risk allocation between producers, consumers, and governments in the scaling up of production or consumption. Effective subsidies, policies, and regulatory frameworks will be necessary to build trust and incentivize large-scale investments in hydrogen infrastructure and production. Such interventions necessitate political decisions that hinge on societal consensus [139,150]. A collaborative approach involving stakeholders from various sectors, policymakers, and the general public is essential to develop and implement effective policies, initiatives, and strategies supporting the further maturing of the hydrogen economy.

8. Conclusions

The aim of this paper was first to analyze the historic roots of the hydrogen economy imaginary, and secondly to explore the continuities and discontinuities in the narrative of the hydrogen economy over time. We have traced and analyzed the emergence and evolution of the ideal, from its inception in the 1970s to the present, dividing its history into three distinct ‘Waves’ of interest, with the Third Wave currently on the rise. We began by analyzing the historical developments towards the First Wave, when scientific advances in hydrogen-related technologies and the prevailing faith in science and technology for societal advancement following the post-war period combined into the concept of a hydrogen economy as the answer to emerging political, economic, and environmental concerns. Additionally, we have found that the appeal of the hydrogen economy stemmed from its alignment with the existing utopian vision of an atomic society. We show that the hydrogen community regarded hydrogen as the missing link needed to realize the full potential of nuclear energy, offering a solution in particular to the challenge of long-distance transport of energy. But also, by virtue of being a fuel, hydrogen was considered the ultimate replacement for fossil fuels.

While this study provides insights into the evolution of the hydrogen economy, it should be viewed as an exploratory analysis based on a relatively limited set of sources. Our investigation of the First Wave employed a sociotechnical analysis including Vieira’s utopia definition to explore how the Hydrogen Romantics framed the hydrogen economy. This method allowed us to dive deeply into the narratives and motivations that shaped the First Wave. However, this sociotechnical analysis was only applied to key publications from the First Wave. A more thorough analysis of the First Wave would enhance our understanding and increase the potential depth of comparison with the later Waves. As for the Second Wave, we relied on secondary literature due to the already extensive research available. This approach was not feasible for the Third Wave, given its ongoing development.

Additionally, a multimethod literature analysis was executed, which allowed to analyze different sizes of databases on multiple levels of detail. While it is effective for capturing broad trends and key narratives, it has inherent limitations in that it depends on the availability and quality of existing sources. This may lead to biases based on the selection of literature and the interpretations made by previous researchers. Despite these downsides, the approach was well-suited to our goal of providing an exploration of the First Wave and identifying significant continuities and discontinuities across the later Waves. A more comprehensive study, incorporating a broader range of primary sources and secondary literature, could provide further insights into these ongoing dynamics.

We found that the hydrogen economy vision of the First Wave can be characterized as a technocratic worldview with strong utopian aspects. It can be interpreted within Vieira’s utopia framework of dystopian future images, as a technocratic approach to address existential threats and create a better future. We conclude that during the First Wave, the hydrogen economy was not just seen as a solution to the contemporary challenges of the 1970s but as a fundamental, long-term transformation towards a prosperous future without resource constraints. Hydrogen was deemed both a necessary and inevitable development to make the atomic society possible. We also found that there was limited attention to the social and political aspects of a hydrogen economy in the scientific literature from this period. It takes a purely technocratic perspective and views technology as capable of solving complex problems, often downplaying the significance and effectiveness of social and political approaches to solve problems. As a result, we conclude that the techno-utopian narrative for a hydrogen economy can be understood as a sociotechnical imaginary that was ultimately overly idealistic and disconnected from practical realities.

We then turned to the Second and Third Waves. The Second Wave emerged in the mid-1990s and lasted to the late-2000s. It saw a renewed interest in hydrogen as a large-scale alternative energy vector, but with a shifted focus towards near- and midterm implementation, especially with fuel cell vehicles. Other than in the First Wave, a multitude of actors were involved in the Second Wave, notably including governments. The media, though sometimes oversimplifying, fueled public enthusiasm by portraying hydrogen as a clean and environmentally friendly solution. However, despite the initial optimism, the techno-utopian portrayal of hydrogen overlooked practical limitations and potential negative side effects, contributing to its eventual decline.

Since the late 2010s, hydrogen is being reimagined as a substitute for fossil fuels. While during the First Wave, hydrogen was perceived as the primary energy carrier within a nuclear-dominated energy system, the current Third Wave, emphasizes its role as a means of storing the intermittently produced electricity from wind and solar, to act as back-up fuel in the power sector as well as to serve as a carbon-free fuel in other sectors. In our analysis, we noted similar elements in the First, Second, and Third Waves, including an urge to prevent existential threats, a shared pursuit of energy security, a vision of hydrogen as a vector to transport large amounts of energy, and similarities in the envisioned hydrogen supply chains. Similar to the Second Wave, there is strong support for the hydrogen economy by vested groups in the Third Wave, such as the natural gas industry, which aims to maintain its economic position in the hydrogen transition.

However, some differences are visible including the selected energy source for the hydrogen economy, a shift in the perceived existential threat from the depletion of fossil fuels to climate change, a transition from viewing hydrogen as the primary energy vector to considering it as part of a diversified mix, and a shift towards a more mature and pragmatic approach including active planning for the widespread deployment of hydrogen as a key energy vector. We assert that the hydrogen economy has matured over its 50-year evolution through three Waves. Today, it has lost much of the techno-utopian narrative of the First Wave and is becoming part of the real-world solution space for energy system decarbonization, notably for industry. Having said that, traces of techno-utopianism can still be observed in proposals for long-distance hydrogen transport from the renewable-energy-rich Global South to the energy-poor regions in the Global North, half an Earth away.

We conclude that the Third Wave can benefit significantly from the lessons learned in previous Waves. Firstly, accessible, low-cost renewable energy sources are critical to success. Secondly, infrastructure development is essential for enabling hydrogen's widespread use. Thirdly, setting realistic, achievable goals and avoiding over-ambitious promises is crucial to regaining public trust. Hydrogen should be presented as part of a diverse energy portfolio rather than a standalone solution. Alternatives should be included such electrification and energy reduction. Finally, broad-based support, effective policies must be fostered through collaborative efforts across sectors.

Ultimately, while much work remains to be done, the Third Wave holds promise for advancing the hydrogen economy as a key component of a sustainable energy future. By learning from past experiences and adapting strategies to current challenges, the Third Wave has the potential to contribute to fulfilling the broader vision of a cleaner, more sustainable, and resilient energy system.

CRediT authorship contribution statement

Laurens S.F. Frowijn: Writing – original draft, Methodology, Investigation, Conceptualization. **David M. Baneke:** Writing – review & editing, Supervision, Conceptualization. **Gert Jan Kramer:** Writing – review & editing, Supervision, Conceptualization.

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Declaration of competing interest

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

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Data availability

Data will be made available on request.

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