Clarifying Progress and Potential of the Transition to a Hydrogen Economy: A Study of Historical Developments, Societal Perceptions, and Expert Perspectives
（水素社会への移行における進捗と可能性の明確化：歴史的発展、社会的認識、専門家意見の調査）

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Abstract

The potential of the hydrogen economy has emerged as a potential response to global climate change concerns, envisioning a sustainable, decarbonized future energy landscape. While the concept presents a potential pathway towards environmental conservation, its development has been marked by a complex interplay of technical, economic, and sociopolitical challenges. This thesis delves into the social dimension of the hydrogen economy, investigating historical development and societal perceptions among stakeholders.

In examining the historical development of the hydrogen economy from when the term was first coined in 1972 until 2020, the research employs bibliometric and content analyses to map its trajectory. Findings indicate that interest in the hydrogen economy has continued over the past five decades, with a growing number of academic publications, media coverage, and projects. However, this finding alone may not fully capture the relative increase in interest, given that publications in all areas have increased. Various endogenous and exogenous factors have influenced the progress of the hydrogen economy and created hype at different points in time. A hype cycle is an observed pattern characterized by strong and rapid increases, followed by subsequent decreases, in both societal attention to and expectations about a technology. Additionally, the various potential configurations of hydrogen as an energy solution allows people to interpret it based on their own perspectives and agendas, resulting in competing interpretations of what a future hydrogen economy may look like.

Focusing on the Japanese context, a comparative study was conducted to investigate the shifts in societal attitudes towards hydrogen technologies through a community survey and compare the results from a previous survey. The results show a gap in public understanding of hydrogen, with actual knowledge lower than self-reported knowledge. The respondents were divided on their preference for green vs grey hydrogen production, with cost and environment being key factors. Public perception is mostly neutral with more positive than negative responses. However, there is a difference between public understanding of hydrogen production and utilization and the reality. Acceptance for hydrogen applications varies, with transportation receiving the most support. As a result of these consolidated findings, questions have arisen about formulating a necessary strategy to educate the public and offer reliable information

concerning the status of hydrogen technology. Such efforts will enable consumers to make informed decisions regarding hydrogen technologies, which is crucial in promoting wider acceptance and understanding of hydrogen as a future energy carrier.

Drawing from the knowledge of 65 experts across 22 countries, the thesis underscores a significant future role for hydrogen, despite past unimpactful hydrogen interest waves. These experts anticipate the emergence of a hydrogen trade landscape, with countries acting as exporters, importers, or transit hubs. The thesis highlights the need for globally accepted protocols for hydrogen production, transportation, and trade. In the short term, experts are divided on the preferred hydrogen method. However, in the mid and long term, there is a clear consensus among experts that it is preferable to transition towards green hydrogen. Furthermore, recognizing that the shift towards a hydrogen economy requires a multi-dimensional approach, policymakers must adeptly balance technological, economic, political, environmental, and social factors to overcome persistent barriers and fully capitalize on hydrogen's unique potential.

In conclusion, this study provides empirical evidence to support the "false start" notion posited by the IEA [1], as well as IRENA's observation that "Hydrogen has spurred multiple waves of interest in the past without significant impact" [2]. By analyzing annual academic publications, mass media articles, and hydrogen-related projects from 1972 to 2020, the study illustrates the cyclical pattern of rising and falling interest, thereby validating the existence of hype cycles in the development of the hydrogen economy. From an expert perspective, while the majority perceive limited progress in the development of the hydrogen economy, they remain optimistic about its long-term potential, particularly by 2050. This optimism is mirrored in the Japanese community, which has shown a growth in perceived knowledge of hydrogen energy from 2008 to 2022.

The novel contributions of this thesis lie in its multi-stakeholder perspective, temporal focus, and a series of studies that consider various types of data (retrospective publications, community and expert opinions) in the development of the hydrogen economy. Unlike existing studies, this research uniquely integrates a historical overview, as presented in Chapter 3, dating back to the inception of the hydrogen economy in 1972, with contemporary primary data from both community and expert surveys covered in Chapters 4 and 5. This synthesis provides a nuanced understanding of how public and expert opinions have evolved over time, set within a broader historical context. Moreover, the thesis adopts a holistic systems perspective to comprehensively evaluate the entire hydrogen supply chain, from production to distribution, offering intricate details about its development and implementation. Lastly, the study serves as a real-time snapshot of current perspectives, laying the groundwork for future academic inquiries, policymaking, and industry strategies. This multi-pronged approach not only fills a gap in the existing literature but also yields valuable insights that can significantly inform future policy decisions, industry initiatives, and research directions in the development of the hydrogen economy.

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I would like to extend my heartfelt acknowledgments to several individuals who have played pivotal roles in the completion of this thesis.

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LIST OF ABBREVIATIONS

Analytic hierarchy process	AHP
Basic Hydrogen Strategy	BHS
Carbon capture and storage	CCS
Clean Urban Transport for Europe	CUTE
Distribution System Operator	DSO
Ecological City Transport System	ECTOS
Electric vehicle	EV
European Hydrogen and Fuel Cell Association	EHA
European Union	EU
Fuel Cell Commercialization Conference of Japan	FCCJ
Fuel cell electric vehicle	FCEV
Fuel Cell Technologies Program	FCT
Fuel cell vehicle	FCV
Gasoline energy system	GES
Hydrogen Council	HC
Hydrogen energy system	HES
International Association for Hydrogen Energy	IAHE
International Energy Agency	IEA
Intergovernmental Panel on Climate Change	IPCC
Lithium-ion battery	LIB
Ministry of Economy, Trade and Industry	METI
Multi-criteria decision making	MCDM
Natural gas reforming	NGR
New Energy Development Organization	NEDO
Non-economic barrier	NEB
Photoelectrochemical	PEC
Polymer electrolyte fuel cell	PEFC
Proton exchange membrane fuel cell	PEMFC
Strengths, weaknesses, opportunities, and threats	SWOT
Sustainable Transport Energy for Perth	STEP
Thermochemical hydrogen technologies	TCH
U.S. Department of Energy	DOE
United Nations Framework Convention on Climate Change	UNFCC
Water electrolysis	WE
World Energy Network	WE-NET

Chapter 1 Introduction

1.1 Background

The usage of hydrogen as an inexhaustible source of fuel was described in Jules Verne's 1894 novel "Mysterious Island" long before it was considered a possible solution to the energy crisis of the current era [3], [4]. In the lower atmosphere, hydrogen is found only in minor concentrations. It is most commonly bonded with other elements such as oxygen to form compounds such as water [5]. Hydrogen can be produced from diverse resources, from fossil fuel resources to renewable resources such as solar or wind energy [1]. Hydrogen's flexibility & possible environmental benefits make it an ideal future energy carrier.

John Bockris first coined the term "Hydrogen Economy" in 1972 to describe a future in which we use hydrogen as an alternative to fossil fuel [6]. The original vision of a hydrogen economy was conceptualized at a time when concerns about fossil fuel depletion in the face of exponential growth in global primary energy use and the associated rising pollution levels were being highlighted [7]. During this initial conceptualization of the hydrogen economy, hydrogen was conceived as playing the critical role of a universal energy carrier. Energy carriers are substances or fuels that store, transport, and deliver energy in a form that can be easily utilized, such as electricity, hydrogen, or liquid fuels (gasoline, diesel and kerosene etc.). They occupy intermediate steps in the energy-supply chain between primary energy sources and end-use applications. Based on an Intergovernmental Panel on Climate Change (IPCC) report on mitigation of climate change, "An energy carrier is thus a transmitter of energy" [8]. Hydrogen was expected be economically produced using nuclear and solar energy, and distributed and utilized across various sectors effectively [9], [10]. In recent years, the role of hydrogen has expanded to provide energy storage that would allow continuous base-load electricity supply in a system relying substantially on intermittent renewable energy resources such as solar and wind energy [11].

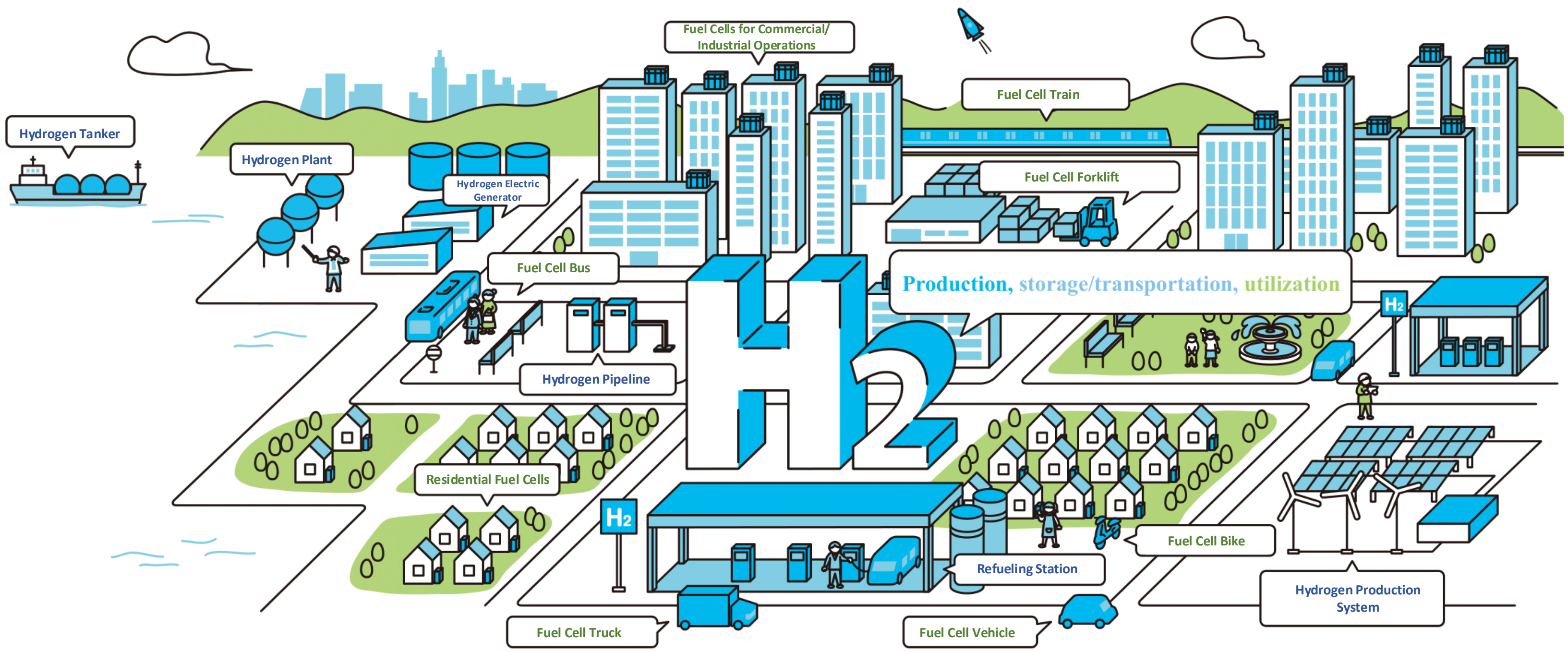

Figure 1: The concept of a hydrogen economy (Redrawn by author) [12]

Figure 1 illustrates the concept of a hydrogen economy. The hydrogen economy is a vision of the future where hydrogen serves as a widespread energy carrier, encompassing production, transportation, storage, and utilization [13]. Hydrogen production methods include steam methane reforming, electrolysis, biomass gasification, and thermochemical processes [14]. Once produced, hydrogen can be transported through pipelines, liquid hydrogen carriers, or as ammonia, among other options [15]. To address the challenge of hydrogen's low density, storage methods include compressed hydrogen, liquid hydrogen, and metal hydrides. In end-use applications, hydrogen shows great promise, from powering transportation through fuel cells for generating electricity in gas turbines or fuel cells for grid stability and off-grid use [1]. Additionally, hydrogen can replace fossil fuels in industrial processes and be utilized for heating and residential purposes [16]. This concept of the hydrogen economy holds tremendous potential to drive sustainability, reduce greenhouse gas emissions, and transform energy systems worldwide.

1.1.1 Global Hydrogen Economy

Global events, most notably the concern over environmental degradation at the local scale and climate change at the global scale [17], geopolitical disruption of the energy supply [18], volatile fossil fuel prices [19], and recent growth of clean technology innovation [18] have reenergized sociological and economic interest in cleaner energy systems including options such as a hydrogen economy [20]. Ever since the term hydrogen economy was coined, it is generally agreed that interest in hydrogen as an energy carrier and the hydrogen economy has at times grown stronger and weaker. In the past five decades, there have been multiple attempts to drive a global hydrogen economy, but the hydrogen economy has not yet happened to any significant extent, and enthusiasm declined [21]. However, post-COVID-19 momentum has created a renewed interest by governments and energy organizations to put hydrogen forward as a major candidate to decarbonize the economy [22]. The pandemic has devastated the global economy and many lives, but the recovery phase presents an opportunity for the energy sector to capitalize and pave the way for green hydrogen that complements renewables [23], [24]. However, it is yet to be seen if tangible progress will materialize as a result of this current wave of interest.

Table 1: A summary of the efforts made by countries in developing their hydrogen strategies [25]

	Policy discussions, official statements, initial demonstration projects			Strategy in Preparation	Strategy Available
Africa	Cape Verde Burkina Faso	Mali Nigeria	South Africa Tunisia	Egypt Morocco	
Asia	Bangladesh	Hong Kong	India	China Singapore New Zealand Uzbekistan	Australia (2019) Japan (2017) South Korea (2019)
Europe	Bulgaria Croatia Czech Republic Estonia Finland Georgia	Greece Iceland Latvia Lithuania Luxemburg Malta	Romania Serbia Slovenia Switzerland Turkey Ukraine	Austria Belgium Italy Poland Russia Sweden Slovakia United Kingdom	European Union (2020) France (2020) Germany (2020) Netherlands (2020) Norway (2020) Portugal (2020) Spain (2020) Hungary (2020)
Latin America & the Caribbean	Argentina Bolivia Trinidad & Tobago	Panama Paraguay	Peru Costa Rica	Brazil Colombia Uruguay	Chile (2020)
Middle East & Gulf States	Israel	UAE		Oman Saudi Arabia	
North America	Mexico	USA			Canada (2020)

Table 1 summarizes the efforts made by countries in developing their hydrogen strategies [25]. The development of a hydrogen economy remains in its early stages, with only a few countries having published their strategies. However, there is broadening global interest and support in this area. Currently, 12 countries, along with the European Union (EU), have published their national hydrogen strategies. Moreover, 19 other nations are in the process of drafting their strategies, with plans to release them in the near future. This increasing government interest is driven in part by the urgency to address global climate issues [25]. Several countries have emerged as key influencers in shaping the hydrogen landscape. Japan published a national hydrogen strategy in 2017 [26] and updated it in 2023 [27], with subsequent heightened interest in the Asian-Pacific region. Following Japan's lead, South Korea [28] and Australia [29] developed their hydrogen strategies shortly after. In Europe, Germany took the lead, encouraging the EU to establish its hydrogen strategy during its EU presidency [25]. In Latin America, Chile stands out as the first country to have a national hydrogen strategy, with numerous other Latin American countries (Brazil, Colombia, Uruguay) planning to follow suit in developing their respective hydrogen strategies. These developments signify a clear acceleration of efforts towards hydrogen integration in national energy policy, underlining the growing importance of hydrogen as an energy solution on the global stage.

1.1.2 Japan Hydrogen Economy

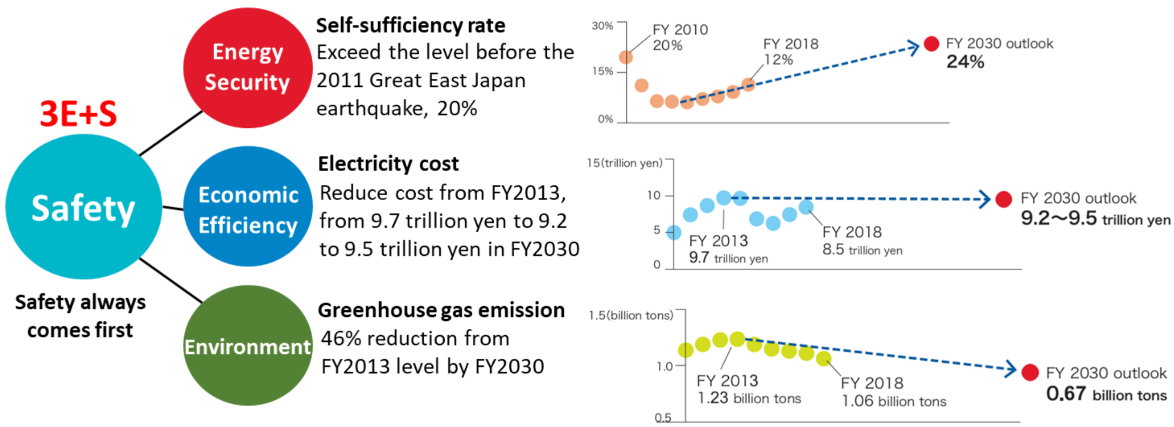

Figure 2: Japan 3E+S national policy (Redrawn by author) [30]

Japan's energy policy is based on the principle referred to as “3E+S” that resonates with its unique challenges and aspirations [31]. 3E+S represents "Energy Security", "Economic Efficiency", "Environment", and "Safety". As show in Figure 2, this policy guides Japan's strategic choices in the energy sector based on three primary objectives: increasing self-sufficiency rate, reducing electricity costs, and lowering greenhouse gas emissions.

One of the cornerstones of Japan's energy policy is to ensure energy security. Given that Japan's fossil fuel dependency was 85.5% in 2018 [30], achieving a consistent and uninterrupted supply is of paramount importance. To address this, Japan focuses on diversifying its energy sources and forming stable relationships with energy exporting countries. Japan aims to ensure that its energy supply is cost-effective, which, in turn, helps maintain and improve the competitiveness of Japanese industries in the global marketplace. Efficient energy pricing and market mechanisms play a role in achieving this objective. As climate change remains a critical global concern, Japan's commitment to the environment is integral to its energy strategy. The country is steadfast in its efforts to reduce greenhouse gas emissions and minimize its overall environmental impact. This is manifested in its increasing shift towards renewable energy sources, conservation measures, and active participation in global environmental protection initiatives [32].

The Fukushima Daiichi nuclear disaster in 2011 indelibly underscored the importance of safety in Japan's energy considerations. Subsequently, "Safety" was added as a foundational pillar of the nation's energy policy [31]. This addition led to a renewed focus on the safety protocols associated with energy generation and distribution, especially concerning nuclear power. Japan has since introduced more stringent safety standards and adopted a more prudent approach to its nuclear energy operations.

In essence, Japan's 3E+S policy provides a holistic framework, melding historical lessons with current global pressures, to chart a comprehensive energy strategy for the nation. Within this context, hydrogen emerges as a pivotal element: it's the lightest flammable gas but, when managed appropriately, has a minimal risk; it offers a means to diversify and transform imported energy sources, reducing procurement risks; as production costs decrease, hydrogen has the potential to reduce energy expenses; and through carbon capture and storage (CCS) and renewable energy methods, it can be produced without carbon emissions [26]. For Japan, a hydrogen-based society is a strategy to achieve 3E+S.

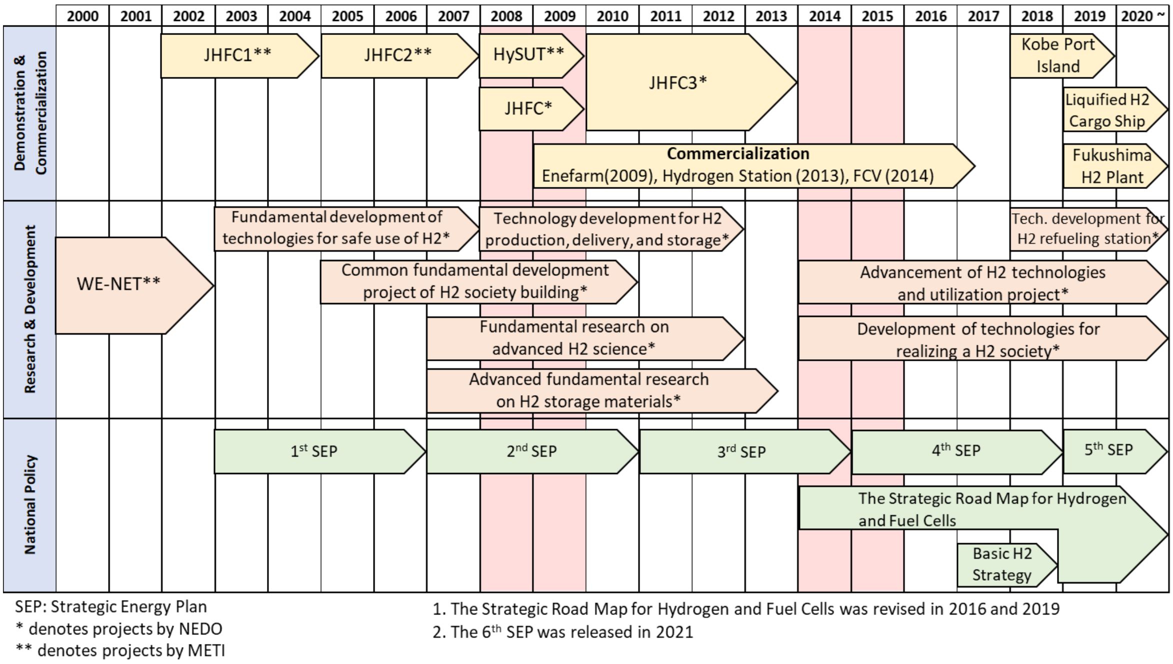

Figure 3: Summary of Japan's Hydrogen Economy Development (Redrawn and updated by author) [33]

Japan has a long history in leading hydrogen innovation with the initiation of the "Sunshine Project," a program introduced by the Japanese government in 1974 and implemented by the government corporation, New Energy Development Organization (NEDO) in 1980 [34]. The national program objective is to develop new energy technology - mainly solar energy, geothermal energy, coal energy, hydrogen energy, and supporting research [35]. In 1993, The New Sunshine Project was established, integrating the existing Sunshine Project (development of new energy technology) and the Moonlight Project (development of energy-saving technology) to promote sustainable growth and concurrently solve the energy crisis and environmental issues. The New Sunshine Project includes multiple programs that focus on hydrogen, including the "World Energy Network" (WE-NET), which ran from 1993 to 2002. As shown in Figure 3, the WE-NET project was a long-term plan to create a global energy network by using hydrogen produced by renewable energy [36], [37]. The WE-NET project was succeeded by the "Fundamental development of technologies for safe use of hydrogen infrastructure" which ran from 2003 to 2007, and subsequently the "Development of technologies for hydrogen production, delivery and storage systems", which ran from 2008 to 2012. In 2014, the Ministry of Economy, Trade and Industry (METI) announced the "Strategic Roadmap for Hydrogen and Fuel Cells" to accelerate realizing a hydrogen-based society [38]. In 2015, the ratification of the Paris Agreement further bolstered Japan's plan of a hydrogen-based society to address critical climate change issues by limiting global warming to well below 2°C [39].

As the energy sector continues to evolve, the roadmap along with technology milestones have been revised in 2016 [40] and 2019 [41] to establish achievable targets considering international cooperation, technology advancement, and societal needs [42]. Despite the continuous effort by the Japanese government to drive the hydrogen transition, the realization of a hydrogen-based economy is still far off in terms of cost-effective and wide-scale deployment [43]. As shown in Table 2. There are significant mismatches between the present situation surrounding the hydrogen economy and previously proposed milestones that are far from being reached. In 2002, the Fuel Cell Commercialization Conference of Japan (FCCJ) [44] projected five million fuel cell vehicles (FCVs) by 2020, while the Japanese government, in a more conservative projection, forecast forty thousand FCVs by 2020 in their 2017 report [26]. However, the International Energy Agency (IEA) reported that there were only over six thousand six hundred FCVs on the road in Japan in 2021 [45]. The disparity between projected targets and actual progress, as evidenced by the significant gaps highlighted in Table 2, emphasizes the complexity of achieving the envisioned targets.

Table 2: Mismatch of previously declared targets and present situation of hydrogen technologies in Japan

		Previously Declared Targets		Future Projection	Current Progress
		2010	**2020**	**2030**	**2021**
Fuel Cell Vehicles [vehicles]	FCCJ	50,000	5,000,000	-	**5,600**
	BHS	-	40,000	800,000	
H2 Stations [stations]	FCCJ	-	4,000	-	**147**
	BHS		160	900	
Residential Fuel Cell Systems [units]	FCCJ	2,200,000	10,000,000	-	**402,039**
	BHS	-	-	5,300,000	

BHS: Basic Hydrogen Strategy
FCCJ: Fuel Cell Commercialization Conference of Japan

1.2 Research Question and Aim

The concept of a hydrogen economy has existed for several decades. However, its journey has been marked by varying degrees of enthusiasm, significantly influenced by fluctuations in energy prices, technological developments, and competing energy alternatives. The prospect of a hydrogen economy brings forth numerous challenges spanning technical, economic, policy, and social dimensions. While these dimensions are all crucial, this research places particular emphasis on the social dimension, seeking to understand stakeholders' (including communities, academia, industry professionals, and policymakers) perceptions and societal implications. Hence, the research questions for this study were as follows:

1. How has the hydrogen economy developed over time, and are there varying expectations among different stakeholders?

2. How have the attitudes of general public towards the hydrogen economy shifted when comparing past perspectives to the present?

3. Considering expert opinions, how does the present state of the hydrogen economy relate to its historical trajectory in terms of challenges, opportunities, and progress?

Thus, the overall aim of this study is to understand how the hydrogen economy has progressed, assess its present status through stakeholder perspectives, and evaluate its prospects for future development. To achieve this, the study clarifies societal perceptions and various interpretations, focusing on historical development, shifting public attitudes toward hydrogen technologies, and expert opinions on transition dynamics.

1.3 Contributions of Study

This thesis aimed to conduct a comprehensive analysis of the transition to a hydrogen economy. To achieve this, the study provides a detailed overview of the hydrogen economy through historical, public, and expert perspective. This thesis methodically examines these aspects through a rigorous historical analysis and two survey questionnaires. The novel contributions of this thesis are as follows:

1. **Historical Overview of the Hydrogen Economy**
   This study contributes by conducting a thorough analysis of the historical development of the hydrogen economy since its inception in 1972. By tracing the evolution of the hydrogen economy over time, the study sheds light on the various hype cycles and significant events that have shaped the perception of hydrogen as an energy carrier. Understanding the historical context is crucial in recognizing how perceptions of the hydrogen economy have evolved and how they might continue to evolve in the future.

2. **Primary Data Collection**
   - **Community Survey**: This provided insights into the public attitudes of the hydrogen economy from a Japanese context, highlighting a knowledge gap, a degree of optimism, and the necessity for effective communication strategies to bridge this gap.
   - **Expert Survey**: Through this study, expert opinions on the hydrogen economy were revealed, showcasing a cautiously optimistic outlook for the future. It also identified past and current challenges as well as benefits from an expert perspective.

3. **Holistic Systems Temporal Perspectives**
   The study adopts a system perspective, evaluating the entire hydrogen supply chain from production to distribution. This approach delves deep into the intricacies of the hydrogen economy, focusing on its development and implementation. To further this understanding, the study emphasizes temporal perspectives designed to capture the nuanced evolution of attitudes and opinions over time.

4. **Record for Current Perspective of Hydrogen Economy**
   The study acts as a snapshot of the present perspectives on the hydrogen economy. This offers a foundation for future research, allowing scholars, policymakers, and industry experts to track the progress and evolution of the hydrogen economy over time.

In essence, this thesis provides a multi-dimensional exploration of the hydrogen economy, capturing its historical development, current perspectives (both public and expert), and future prospects. It fills a gap in the existing literature by offering a holistic approach, integrating historical analysis, primary data collection, and system evaluation. The results from this research can significantly inform policy decisions, industry strategies, and future research directions in the realm of the hydrogen economy.

1.4 Overview of this work

The overall structure of the main chapters of the thesis is shown in Figure 4.

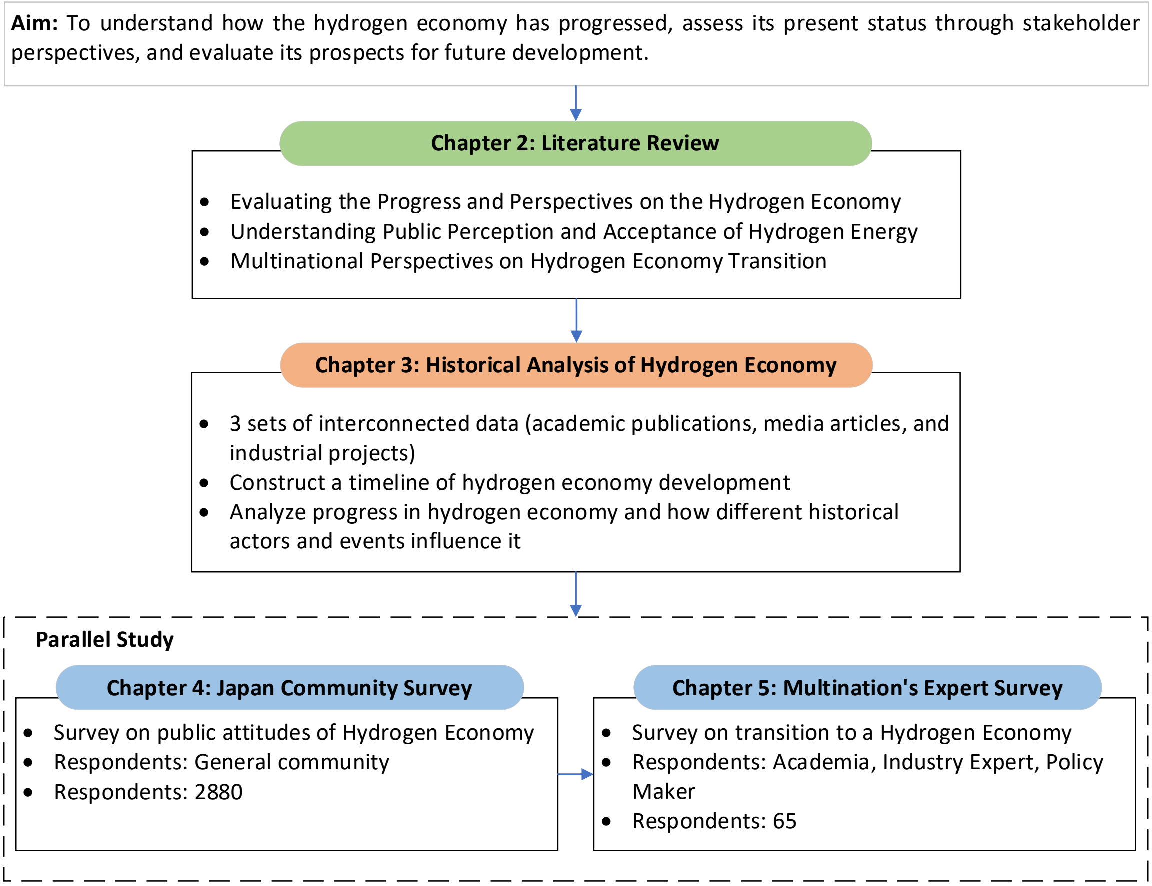

Figure 4: Research Framework

This thesis comprises six chapters. Chapter 1 provides an overview of the research by introducing the concept of the hydrogen economy, highlighting its significance, and discussing its implications for the energy landscape. Additionally, the development of the global and Japanese hydrogen economies will be examined. Concluding this introductory chapter, the research questions and aim will be stated.

Chapter 2 constitutes a literature review that sheds light on the multifaceted nature of the hydrogen economy. It explores its evolution, methodologies employed in related studies, public perceptions of hydrogen technology, and insights from experts. The aim of this literature review is to synthesize the extensive body of knowledge and identify existing research gaps.

Chapter 3 employs content and bibliometric analysis to provide a structured historical narrative of the hydrogen economy. The first study utilizes three sets of interconnected data (academic publications, media articles, and industrial projects) as indicators to report on the progress of the hydrogen economy. Each type of data serves as an indicator, revealing different facets of progress in the hydrogen economy. Academic publications serve as an initial indicator, revealing the emerging research that underpins the field. Industrial projects represent an intermediate stage, often capturing the transition from theoretical research to practical, pre-commercial applications. Meanwhile, media articles act as indirect indicators, reflecting public perception and societal engagement with the hydrogen economy more broadly. Together, these interconnected data sets offer a more complete view of the progress that has shaped the hydrogen economy over time. The results describe changing trends and how specific events or actors have influenced its development, the emergence of hype cycles, and expectations for a future hydrogen economy. The energy transition is a long-term process, linked to a continuous chain of historical events and narratives that extend into the present.

Building on the insights gained from Chapter 3, which examines past narratives of the hydrogen economy through the theoretical frameworks of actors' roles in transitions and the sociology of expectations, the study moves to the assessment of current societal perspectives. This assessment is vital for understanding social support, aligning collective expectations, and tracking progress toward realizing a hydrogen economy in the future.

Chapter 4 presents the findings from a community survey conducted in Japan in 2022, assessing contemporary attitudes towards the hydrogen economy. The results were compared against previous surveys (conducted in 2008, 2009, and 2015) to analyze shifts in knowledge, perceptions, and acceptance over a span of more than a decade. This second study is to understand the current general public's view of the hydrogen economy and to examine whether this perspective differs from those of past cohorts. This change in perception can be attributed to the dissemination of information from academic, media, and industrial sources, which continues until the technology gains widespread acceptance.

Chapter 5 presents the outcomes of an expert survey that captures multination insights into the transition of the hydrogen economy. The focus was on the current progress and future projections, the hydrogen supply chain including trade and production, and the key drivers and barriers for implementing a hydrogen economy, considering both past and present perspectives. The third study seeks to capture the insider perspective - specifically focusing on the opinions of individuals who are closely involved in the hydrogen economy, seeking to understand what these experts identify as the most pivotal factors for the transition to a hydrogen economy.

Chapter 4 and Chapter 5 comprise a parallel study aimed to elucidate the different yet overlapping interpretations of hydrogen economy among different groups of society, mainly academic, industry, government, and the general public as described in Chapter 3. While the community survey, conducted in March 2022, focused on gauging public attitudes of the hydrogen economy, the expert survey carried out in June 2023 included more technical questions relevant to specialists in the field. Consequently, findings from the community survey were incorporated into the expert survey, serving as a basis to solicit expert opinions on the public's understanding and acceptance of the hydrogen economy.

Chapter 6 synthesizes the findings from the preceding chapters to provide conclusive remarks on the overall aim and contribution of the study. Additionally, potential areas for further research will be discussed.

Chapter 2 Literature Review

As introduced in Chapter 1, the global energy landscape is experiencing a transformative shift to a cleaner future. As nations grapple with the pressing imperatives of climate change and energy security, the search for sustainable energy solutions has intensified. At the forefront of this quest lies the hydrogen economy — a concept that utilizes hydrogen as an energy carrier for different sectors complementing electricity. Its potential to reduce carbon emissions, provide energy storage, and fuel transport and industry makes it a pivotal element in future energy strategies. However, while technological advancements and investments in the hydrogen sector continue to grow, understanding its intricate web of societal perceptions, expert opinions, and global development becomes equally vital. These elements collectively shape policy, drive adoption, and influence the strategic positioning of nations, ensuring a holistic and sustainable approach to integrating hydrogen as a cornerstone energy carrier.

A comprehensive review of the literature sheds light on the multifaceted nature of the hydrogen economy: from its evolution and the methodologies adopted in related studies, to the public's perception of hydrogen technology, and finally, to the insights from experts steering its course. This literature review aims to synthesize this vast body of knowledge, identify existing research gaps, and highlight potential pathways for future research, thereby presenting a holistic overview of the hydrogen economy in the current energy transition.

2.1 Evaluating the Progress and Perspectives on the Hydrogen Economy

The history of the hydrogen economy, despite totaling only a few decades since its conceptual expression, can be seen to be complex and evolving. Pioneering authors in the field, Nejat Veziroğlu [46] and John Bockris [47], addressed the turbulent progress of the hydrogen economy from their firsthand experiences at different point of the hydrogen economy. As shown in Figure 11, Nejat Veziroğlu’s article was published in 2000, when the previous wave of hype was rising rapidly, while John Bockris article was published in 2013, after the peak of the previous hype had died down. Despite the articles being published at different time, they concluded that the hydrogen movement had gained momentum over the years and would continue growing in the future. On the other hand, Hultman and Nordlund [48] used historical analysis to explore the expectations of fuel cells in promoting the realization of a hydrogen economy. Their study analyzed press articles, and government reports from 1990 to 2005 to characterize important events and actors influencing the hydrogen economy.

Using the standard literature review process, Solomon and Banerjee [49] surveyed government policies, industry reports, intergovernmental reports from 1998 to 2005 and concluded that although the hydrogen economy concept is more widespread, governments and companies alike had only vague plans for hydrogen development. El-Emam and Özcan [50] systematically reviewed 170 journal papers, analyzing the production cost of hydrogen by different production pathways. In a similar study, McDowall and Eames [51] conducted a systematic review by examining 40 case studies, including governmental policy, journal papers, and industrial reports, against a standard survey template to ensure the data were collected and compared consistently. Their results revealed that each actor group had a different image of a future hydrogen economy rather than a shared vision.

In recent studies, bibliometric analysis has been used to highlight the changing interest in a particular area of study, such as renewable energy [52], carbon capture & storage [53], electric vehicles [54], and also the hydrogen economy [55], [56]. Tsay [57] investigated the characteristics of hydrogen energy publications and the implications by using bibliometric techniques on 14,449 journal papers (from 1965 to 2005). The results indicated that hydrogen energy research has grown exponentially and reinforced the idea that hydrogen energy has a major role in the future energy system. Yonoff et al. [58] investigated the research trends of fuel cell power generation systems using a bibliometric approach on 15,020 journal papers (from 2008 to 2018). A similar overview was presented by Alvarez-Meaza et al. [59], quantifying scientific and technological trends of fuel cell electric vehicle (FCEV) research by analyzing bibliographic information from journal papers and patents. Related to user perceptions of a hydrogen economy, Martin, Agnoletti, and Brangier [60] conducted a bibliometric analysis. As a result, end-users` acceptance was perceived as a barrier to developing a hydrogen energy system.

As bibliometric analysis inherently draws on an extensive data library, there is a possibility to miss relevant publications that did not use the related keywords in the data searching process [61]. Bibliometric analysis is ideal for assessing hundreds or thousands of publications based on metadata information but it lacks depth and a detailed approach in reviewing a publication individually [62]. This inherent limitation of bibliometric analysis can be countered by use in conjunction with a deeper qualitative analysis (content analysis or thematic analysis) or using multiple data streams (patent, mass media, governmental reports). Hence, it is worth noting that several authors have utilized both bibliometric analysis and content analysis to explore research trends and delve deeper into the literature [63]–[65].

A comparison table of the different studies, their methods, datasets, study period, and description of the study on the different aspects of the hydrogen economy is provided in Table 3. These studies address various aspects of the hydrogen economy, such as production, end-use application, and user perception.

Table 3: Summary of Literature Review—Studies analyzing hydrogen technologies and hydrogen economy progress

Ref	Published	Method	Data	Period	Description of Study
[46]	2000	Retold from experience	Mass Media	1972–2000	Progress evaluation of hydrogen economy's knowledge, technological development, and public awareness
[47]	2013	Retold from experience	-	1972–2012	Retelling of the contribution of early advocates of hydrogen economy and how it came about
[48]	2013	Historical Analysis	Press articles Government report Mass media articles	1990–2005	Establish the history timeline of development of fuel cell and expectation of fuel cell technology associated with the vision of a hydrogen economy
[50]	2006	Systematic review	170 journal papers	1970–2019	Analyze the production cost of hydrogen by different pathways important for near term deployment of large-scale hydrogen production
[51]	2019	Systematic Review	Government policies Journal papers Industry reports	1996–2004	Investigate expectations, drivers, barriers, and characteristics of different interpretations of hydrogen economy
[49]	2006	Literature Review	Government policies Industry reports	1998–2005	Survey the global status of hydrogen energy research, development, and different countries policy on hydrogen energy
[55]	2020	Bibliometric analysis	58,006 journal papers	1935–2018	Establish history timeline of hydrogen supply chain by analyzing bibliographic information of journal papers
[56]	2019	Bibliometric analysis	13,915 patents	1998–2018	Explore the research trend of hydrogen economy by analyzing bibliographic information of patents
[57]	2008	Bibliometric Analysis	14,449 journal papers	1965–2005	Quantify the growth of hydrogen energy literature by analyzing bibliographic information of journal papers
[58]	2019	Bibliometric Analysis	15,020 journal papers	2008–2018	Explore the research trend of PEMFC by analyzing bibliographic information of journal papers
[59]	2020	Bibliometric analysis	2514 journal papers 1909 patents	1999–2019	Quantify scientific and technological development of FCEV by analyzing bibliographic information of journal papers and patents
[60]	2020	Bibliometric analysis	152 journal papers	1982–2018	Analyze end-user perception of a hydrogen economy by analyzing bibliographic information of journal papers

2.2 Understanding Public Perception and Acceptance of Hydrogen Energy

Over the past few decades, various studies have investigated the technical and economic aspects of hydrogen as a promising energy carrier to solve global climate issues and increased concerns in the fossil fuel-based energy economy [46], [66]. However, the social aspects, particularly the study of public perception or acceptance of hydrogen, has been significantly less frequent [67].

Country-specific studies such as for Germany [68]–[70], USA [71], [72], England [73], [74], and Spain [75] have investigated the acceptance and implementation of hydrogen technology. In a more localized study, Heinz & Erdmann [76] conducted a questionnaire survey in eight different European cities to compare public attitudes towards hydrogen technologies. In a similar study, Ingaldi and Klimecka-Tatar [77] conducted a survey in three Eastern Europe countries (Poland, Czech Republic, and Slovakia) to investigate public perception of hydrogen energy and fuel cell vehicles. Although they use varying survey designs, the results concluded that the public seems to have a positive impression of hydrogen technology. However, the studies also reveal that the public is largely unaware of hydrogen beyond the automotive sector, and most individuals do not have firsthand experience with hydrogen technology. Aside from perception, personal experience with hydrogen technology can greatly influence the acceptance of hydrogen in daily life [69].

In addition, there are many hydrogen demonstrations or pilot projects involving different sectors and technology types. In some cases, the projects are conducted in parallel with a community survey to evaluate public reactions in experiencing hydrogen in action or as a preliminary assessment of public acceptance for future investment in hydrogen technology. Notable projects include Clean Urban Transport for Europe (CUTE), the largest demonstration project of fuel cell buses in nine different cities within Europe [74], [78], [79], Sustainable Transport Energy for Perth (STEP), an initiative by the Government of Western Australia's Department for Planning and Infrastructure to test three hydrogen fuel cell buses in the city of Perth [80] and Ecological City Transport System (ECTOS), a demonstration project in Reykjavik, Iceland, using fuel cell buses as well [81], [82]. However, the respondents of these studies are often made aware of hydrogen and its benefit, thus leading to potentially biased opinions and selective sampling compared to a random sampling of the entire population [83].

Given the long history of Japan with hydrogen, there have been surprisingly few studies focusing on public perception of hydrogen to date. The few available studies (in Japanese) were carried out by NEDO and Mizuho Information & Research Institute as a nationwide survey conducted in 2008 [84] and 2009 [85], investigating social acceptance of hydrogen. Their results indicated that the public perspective of hydrogen technology is relatively high, although most respondents do not have actual experience using hydrogen technology. Itaoka et al. [86] conducted an updated survey in 2015, comparing the results to those of previous surveys and focusing more on hydrogen in the transportation sector. The study concluded that public knowledge of hydrogen energy, hydrogen infrastructure, and fuel cell vehicles increased significantly compared to previous surveys. In a different study, Ono et al. [87] evaluated the public acceptance of hydrogen stations in Japan using a risk perception scale. Their results showed that providing risk-related information to the public will lead to a higher rate of acceptance.

At present, the majority of studies focus on a single aspect of hydrogen, mainly transportation, often overlooking aspects such as production and storage, which also form the basis of a hydrogen-based economy. This is partly because hydrogen technology is not widely available yet, and most are at prototype or pilot stages, which leads to less public engagement. Furthermore, the potential transition to a hydrogen economy is predominantly discussed among the scientific community [83]. Although hydrogen has been covered extensively by the media over the years, the interest has featured recurring hype, often associated with futuristic technology, environmental issues, and most recently COVID-19 post-economy recovery in the energy sector [22].

Numerous surveys have been undertaken as integral components of research programs supporting the development of regional or national hydrogen pilot studies. Among such programs is the ACCEPTH2 project, a collaboration between four cities across the globe, including London, Munich, Luxembourg, and Perth. The ACCEPTH2 study primarily focused on the attitudes and preferences of bus users [78]. However, the London study encompassed fuel cell vehicles [73] and hydrogen refueling stations [74]. Thesen and Langhelle [88] further extended the ACCEPTH2 study by employing the same set of questionnaires used in the London study [73], but adapted them to the specific objectives of their study, which aimed to compare attitudes towards hydrogen vehicles and refueling stations between Stavanger and London. Another noteworthy program was the U.S. Department of Energy (DOE) Fuel Cell Technologies Program (FCT), which aimed to evaluate individuals' understanding and awareness of hydrogen. This study specifically aimed to determine whether any changes had occurred since the baseline survey conducted in 2004 [71]. To achieve this objective, a second survey was conducted in 2008 and 2009 to provide insights into any shifts or trends that may have occurred since the original survey [72]. The current study follows a similar approach, in that it seeks to compare the results of previous surveys in Japan with the present. Table 4 presents a comparison of these studies, including their method, survey year, location, and summary of their findings on different aspects of the hydrogen economy.

Table 4: Summary of Literature Review – Studies analyzing public perception or acceptance of hydrogen economy

					Technology			Socio-Economic			
Ref	**Survey Year**	**Location**	**Respondent**	**Method**	**Production**	**Storage**	**End use**	**Knowledge**	**Value**	**Perception**	**Acceptance**
[81]	2001	Iceland	1154	Interview			•	•		•	•
[73]	2003	London	414	Interview			•	•	•	•	•
[89]	2003	Netherlands	612	Questionnaire			•	•		•	•
[74]	2003	London	346	Questionnaire		•		•		•	•
[78]	2003-2004	4 cities [c]	1358	Interview			•	•	•	•	•
[79]	2004	Sweden	541	Questionnaire			•	•		•	•
[82]	2004	Iceland	200	Questionnaire			•	•		•	•
[71]	2004	USA	2224	Interview	•	•	•	•	•	•	•
[88]	2006	Norway	1000	Interview			•	•	•	•	•
[76]	2006	Europe	3353	Interview			•	•		•	•
[72]	2008-2009	USA	2825	Interview	•	•	•	•	•	•	•
[84]	2008[a]	Japan	1188	Questionnaire		•	•	•	•	•	•
[85]	2009[a]	Tokyo	800	Questionnaire		•	•	•	•	•	•
[90]	2009	Norway	1000	Interview		•	•	•	•		•
[68]	2010	Germany	1011	Interview			•	•	•	•	•
[91]	2010	Netherlands	1214	Questionnaire		•		•			•
[69]	2013	Germany	1000	Interview		•	•				•
[87]	2014	Japan	2069	Questionnaire		•		•	•	•	•
[75]	2015	Spain	1005	Questionnaire		•	•	•		•	•
[86]	2015[a]	Japan	3133	Questionnaire		•	•	•	•	•	•
[70]	2016	Germany	141	Questionnaire		•		•		•	•
[92]	2018	Turkey	10	Interview				•			
[77]	2019 - 2020	Europe	766	Questionnaire			•	•	•		
-	2022[b]	Japan	2880	Questionnaire	•	•	•	•	•	•	•

[a] Indicates studies used for comparison
[b] Indicates current study
[c] The 4 cities are London, Munich, Luxembourg, and Perth

2.2.1 Closing Remarks

Despite significant efforts made to explore the potential of a hydrogen economy, there remain notable gaps in research. One such gap is the limited number of studies evaluating public perception and acceptance of hydrogen from a system perspective, considering all stages from production to end-use applications. Therefore, more comprehensive studies that take a holistic approach to examining public attitudes toward a hydrogen economy are needed. Another gap in current research is the limitations of survey-based methodology in providing a comprehensive understanding of changing attitudes over time. Aside from the study conducted by the DOE, all other studies only capture public attitudes at a single point in time without being compared with similar studies conducted in the same location. Survey-based methods tend to rely on a static snapshot of public opinion and may not capture the dynamic changes in attitudes over time [93], which are essential for understanding the evolution of acceptance of hydrogen and its technologies. Thus, a need exists for more longitudinal and in-depth research that considers various factors influencing public attitudes toward a hydrogen economy.

Numerous reviews have analysed public attitudes towards hydrogen and its technologies by summarizing findings from previous studies considering the perspectives of the general public, experts, and early adopters of hydrogen technologies [83], [94]–[96]. In this sub chapter, 23 studies were selectively included for comparison to ensure relevance to our study boundary. Over the years, 11 studies have used the interview method, while 12 studies have used the questionnaire method. The majority of the studies were concentrated in Europe, with 11 studies conducted in various European countries. Two studies were carried out in the United States, and Japan was the only Asian country represented in the studies. Other countries that were included in the studies were Iceland, Sweden, Norway, and Turkey.

2.3 Multinational Perspectives on Hydrogen Economy Transition

In recent years, a growing body of literature has examined community stakeholders' experiences, perceptions, and expectations regarding the development of the hydrogen economy as reviewed in Section 2.2. Although these studies provide valuable insights, they often overlook the perspectives of experts who play a critical role in shaping public policies, strategies, and investment in the hydrogen value chain. Recognizing this gap in the literature, a critical review has been conducted to evaluate the academic scholarship dedicated to understanding the hydrogen economy through expert survey-based studies. By conducting a comprehensive analysis of peer-reviewed articles using Scopus document analysis, the literature review established the current state of knowledge on the topic, identifies the key themes and findings of expert survey-based studies, and sheds light on the research gaps, providing a comprehensive background for our study. The papers were classified into three thematic groups, which are described in Table 5, Table 6 and Table 7. The studies denoted with an asterisk (*) in the year column signify that survey questions were presented in those studies and have been used as a reference for the survey questionnaire implemented in this study.

2.3.1 Insights from Hydrogen Economy Studies in National Context

The first set of thematic papers relate to national-level studies in specific countries. Table 5 summarizes these studies, which focus on future expectations, characteristics, socially integrated risks, and stakeholder perspectives in various countries.

Table 5: National Level Hydrogen Economy Studies

Year	Theme	Description of Study	Ref
2010*	Hydrogen Economy	Investigate the expectations for the future of the technological advancements in hydrogen in Turkey	[97]
2016*	Hydrogen Economy	Identify characteristics of hydrogen economy in China and recommend strategies for advancing its progress	[98]
2020	Hydrogen Economy	Evaluate the socially integrated risks related to the adoption of a hydrogen energy system and compared it to a gasoline energy system in Japan	[99]
2022*	Hydrogen Economy	Comprehend the perspective of the primary stakeholders of the hydrogen economy in Brazil	[100]

The hydrogen economy has garnered increasing attention as a potentially sustainable alternative to traditional energy systems [101]. Researchers across the globe have sought to understand the potential of hydrogen as an energy carrier, as well as the challenges and opportunities it presents. For example, Celiktas and Kocar [97] employed a two-round Delphi survey method to investigate the expectations of sector representatives regarding the future of technological advancements in hydrogen in Turkey. The survey involving 60 experts from 18 different locations revealed that the hydrogen economy has the potential to foster innovation and economic prosperity if supported by appropriate policies. In a similar study, Ren et al. [98] aimed to help stakeholders understand the current state of the hydrogen economy in China by utilizing a two-round Delphi method with 67 experts in the first-round questionnaire and 10 experts in a second-round discussion. Through a strengths, weaknesses, opportunities, and threats (SWOT) analysis, they identified 12 critical factors and subsequently employed multi-criteria decision making (MCDM) to recommend and prioritize nine effective strategies in roadmap planning, budget planning, and resource allocation for promoting the hydrogen economy in China.

While these studies focus on the prospects and strategies for hydrogen economies in different countries, Hienuki et al. [99] surveyed 13 experts with engineering or social science backgrounds to examine the social implications and potential risks of adopting a hydrogen energy system (HES), comparing it to a gasoline energy system (GES). The results revealed notable differences between HES and GES in terms of price and convenience, along with differing opinions among experts across engineering and social sciences, and even disagreements within the same field. In a more comprehensive study in 2022, Chantre et al. [100] utilized a combination of literature review, document analysis, interviews, and questionnaire-based surveys involving 32 experts to comprehend the perspective of the primary stakeholders of the hydrogen economy in Brazil. The study found that decarbonization is the main driver for the development of the hydrogen economy in Brazil. However, there is a difference in opinion between policymakers and the industry regarding the timeline for achieving a hydrogen economy, with policymakers aiming for the medium term (6-10 years) and the industry predicting the long term (more than 11 years) based on technical and economic projections.

2.3.2 Insights from Hydrogen Production Studies

This section, starting with Table 6, summarizes key assessments of different production methods, benefits of cooperation, renewable hydrogen storage, and overcoming barriers to hydrogen technology deployment.

Table 6: Hydrogen Production Studies

Year	Theme	Description of Study	Ref
2014	Hydrogen Production	Assesses seven hydrogen production methods considering technical features, cost-effectiveness, market potential, and local R&D status, for short, medium, and long-term periods	[102]
2014	Hydrogen Production	Examines the potential benefits of cooperation among Danish energy and electricity stakeholders, considering their influence and the complex dynamics in transitioning to a fossil-free society	[103]
2016	Hydrogen Storage	Examines renewable hydrogen storage use in Europe, considering location, policy, and economic aspects to optimize storage amid fluctuating electricity demand	[104]
2017*	Hydrogen Infrastructure	Evaluates five non-economic barriers to the deployment of hydrogen technology in Europe, and propose appropriate measures to overcome them	[105]
2022	Hydrogen Production	To reach a basic agreement on strategically enabling large-scale green hydrogen demonstrations, followed by commercialization, in China	[106]

As the global interest in hydrogen production intensifies [107], it is crucial to examine the multitude of factors that contribute to the development and adoption of hydrogen technologies in different regions. Enevoldsen et al. [103] conducted an initial study in the Danish energy and electricity industries, identifying 35 stakeholders and assessing their influence while exploring potential cooperation between the sectors. The study found that stakeholders with the most significant impact on the hydrogen industry were either complementors or customers for developing electrolysis plants, indicating support for efficient electrolyzer plants within the Danish electricity industry.

In the context of hydrogen production technologies in Korea, Chung et al. [102] surveyed 32 experts, comprising R&D professionals and policy professionals, using the analytic hierarchy process (AHP) to evaluate various technologies in terms of technical characteristics, economic efficiency, marketability, and domestic R&D conditions across different timeframes. The study found that natural gas reforming (NGR) was expected to lead the technology market in the near term due to its cost competitiveness. However, there was a difference of opinion between the professional groups in the mid-term. While R&D professionals predicted that water electrolysis (WE), thermochemical hydrogen technologies (TCH), and photoelectrochemical (PEC) technologies would continue to be enhanced and rapidly replace NGR, policy experts predicted that NGR would maintain its competitive edge and share the hydrogen production market leadership with WE in both the mid-term and long-term. Meanwhile, Li et al. [106] aimed to address knowledge gaps surrounding the development of a strategic roadmap for large-scale green hydrogen demonstrations and commercialization in China, surveying 83 experts from government, industry, and academia using the Delphi method and SWOT analysis. The survey, conducted in 2021, suggested that although green hydrogen is not expected to be cost-competitive within the next five years, its large-scale implementation is crucial for decarbonizing China's economy. This requires significant technological advancements across the supply chain, as well as the establishment of flexible regulations and appropriate standards.

Bridging these regional studies, it is apparent that the landscape of hydrogen production and utilization varies significantly across countries, which necessitates a tailored approach to overcome unique challenges and capitalize on opportunities within each region. Similarly, research into the European context for renewable hydrogen storage offers valuable lessons on effectively integrating hydrogen technologies into existing energy systems, while addressing the potential barriers that may impede their widespread adoption. Garcia et al. [104] conducted an expert opinion survey, consulting 33 organization members from the European Hydrogen and Fuel Cell Association (EHA) and Distribution System Operators (DSOs), comprising academics and industrial experts. The study aimed to identify potential uses of renewable hydrogen storage systems in Europe, analyzing factors such as location, regulatory frameworks, government perspectives, and economic concerns. It emphasized strategies and actions to optimize hydrogen storage from renewables to mitigate the adverse impact of fluctuating electricity demand and generation due to rising shares of renewables in European countries' energy mix. In a follow-up study with the same expert panel, Astiaso Garcia [105] evaluated the impact of five non-economic barriers (NEBs) potentially hindering the deployment of hydrogen technologies and infrastructures in Europe, and proposed suitable measures to address them. The survey results indicated that a top-down approach, in which experts such as academics and industrial professionals play a pivotal role in communicating hydrogen's potential to decision-makers at local and national levels, is the most effective strategy for promoting hydrogen use in current and future energy markets.

2.3.3 Insights from Hydrogen End-Use Studies

The third thematic set of papers are summarized in Table 7. This section examines studies on fuel cell technologies, implementation, and barriers to hydrogen-based end-use technologies, such as hydrogen transportation.

Table 7: Hydrogen End-Use Studies

Year	Theme	Description of Study	Ref
2004	Polymer Electrolyte Fuel Cells	Assess R&D investment's effect on reaching performance and cost goals for stationary and automotive PEFC applications	[108]
2008	Hydrogen Transportation Technology*	Determine barriers hindering the widespread adoption of hydrogen transportation technology in China, Japan, North America, and Europe	[109]
2021*	Fuel Cell Vehicles	Compare the drivers and barriers affecting the production and adoption of fuel cell vehicles and electric buses	[110]
2022*	Fuel Cell Technologies	Identify and categorize the barriers hindering the advancement of hydrogen fuel cell energy in South Korea	[111]

* refers to hydrogen storage, fuel cell, small scale hydrogen transportation

In recent years, fuel cell technology has been garnering increased interest among researchers [58], leading to numerous studies aimed at understanding the barriers and challenges that hinder its widespread adoption. In 2003, Kosugi et al. [108] investigated the impact of R&D investment on the time required to achieve performance and cost targets for polymer electrolyte fuel cells (PEFC) in both stationary and automotive applications. Surveying 71 experts, they found that the estimated time to reach these targets was around 17 years, or by 2020. In a 2008 study, Hart et al. [109] focused on the potential obstacles to the widespread adoption of hydrogen technology in transportation across China, Japan, North America, and Europe. In a single round of interviews designed to resemble the Delphi methodology, 49 experts identified the most significant barriers as: the need for coherent policy development, the performance of hydrogen storage technologies, and cost. Despite these challenges, experts believed that hydrogen fuel cell vehicles could be on the road in tens of thousands within 5 years, with full commercialization achievable within 10-15 years. Trencher and Edianto [110] similarly used a two-stage Delphi method to compare the drivers and barriers affecting the production and adoption of fuel cell vehicles (FCEVs) and electric buses (FCEBs). Their study, involving 28 respondents in the questionnaire stage and 17 in the interview stage, found that high costs of vehicle production and refueling stations, limited vehicle supply, and inadequate availability of refueling stations were key challenges, despite strict environmental regulations and government-funded programs promoting innovation. Lastly, Lee et al. [111] utilized Delphi surveys and AHP techniques to identify five key perspectives on the barriers to the development of hydrogen fuel cells, which included social, technological, economic, ecological, and institutional and political factors. Among the 40 experts involved, they determined that the most critical barriers were related to institutional and political factors, with the cost of the fuel cell unit and infrastructure also posing significant challenges.

2.3.4 Closing Remarks

While the studies presented in this review provide valuable insights into the complexities and potential of the hydrogen economy within various national contexts, several research gaps can be identified. First, there is a need for a more comprehensive understanding of the global hydrogen economy by comparing and contrasting findings from different countries. The only studies taking into account multiple countries have been conducted by Garcia et al. in Europe [104], [105] and Hart et al. [109] in four different regions. Such international comparisons would enhance our understanding of the unique challenges and opportunities faced by different countries, and aid in identifying best practices and lessons learned from each one. Given that every nation has its own unique resources, opportunities, and challenges, it is unsurprising that tailored strategies are essential to address specific barriers and capitalize on potential advantages within each country.

The studies further demonstrate that there are diverging opinions and disagreements among experts from various fields and within the same fields, emphasizing the multifaceted nature of the challenges and opportunities associated with the hydrogen economy, as highlighted in our review of studies [99], [100], [102]. Each expert brings a unique background and knowledge base, contributing to diverse perspectives on the structure and implementation of a hydrogen economy [112]. Furthermore, the discrepancies in projected timelines for the realization of the hydrogen economy, as identified in some studies we reviewed [100], [108], [109], indicate the necessity for continuous research, collaboration, and dialogue among stakeholders to ensure a smooth and sustainable transition towards this emerging energy landscape. Numerous other studies have also highlighted the mismatches between hydrogen roadmap targets and the current state of fuel cell vehicle adoption [113], [114].

Lastly, while some studies have explored expert opinions on the drivers and barriers to hydrogen technology adoption [105], [110], [111], the dynamic nature of energy transition [115], [116], including the emergence of a hydrogen economy, requires ongoing investigation. Factors such as technological advancements [56], policy changes [117], [118], and shifts in public perception [86], [119] can potentially alter the landscape of hydrogen technology adoption over time. To gain a more comprehensive understanding of the current situation, it is important to focus on examining how these factors have evolved or changed since their last assessment, as well as identifying any new or emerging drivers and barriers. In doing so, stakeholders can better anticipate and address the challenges and opportunities that lie ahead for the successful integration of hydrogen technology into the global energy system.

This review emphasizes the importance of consolidating a multitude of perspectives when devising strategies for the development and adoption of hydrogen technology. Such strategies must consider the evolving dynamics across various regions and timeframes, reflecting the vital role of global collaboration in driving the hydrogen economy. Notably, the drivers, barriers and the very concept of a hydrogen economy are not fixed, having transformed over the years in response to changing circumstances.

2.4 Summary & Addressing Research Gaps

In this chapter, the literature on the hydrogen economy is synthesized, emphasizing the challenges of transitioning towards a sustainable hydrogen-driven future. The review highlights the interplay between global development, societal perceptions, and expert opinions, revealing the intricate web that characterizes the evolving hydrogen landscape. As the world pivots towards more sustainable energy solutions, it is essential to continue fostering a comprehensive understanding, ensuring that future research, policy, and practice are informed, nuanced, and poised to address both the challenges and opportunities that lie ahead in the hydrogen economy.

Summary of Each Section:

1. Evaluating the Progress and Perspectives on the Hydrogen Economy: This section provides a comprehensive overview of the hydrogen economy's evolution. It studies a wide range of literature covering the development, research trends, and opportunities associated with hydrogen as an alternative energy source. Additionally, it examines the methodologies used in these studies, offering insights into the effectiveness of different research methods.
2. Understanding Public Perception and Acceptance of Hydrogen: This section focuses on the social aspects of the hydrogen economy, specifically examining public perception and acceptance of hydrogen technology. It reviews studies that explore the knowledge, attitudes, and perceptions of the public towards hydrogen technology and the factors influencing its acceptance.
3. Multinational Perspectives on Hydrogen Economy Transition: This section reviews studies based on expert opinions on the hydrogen economy. It encapsulates studies exploring expert perspectives on various aspects, such as strategies to promote the hydrogen economy, challenges and opportunities, and policy recommendations.

The transition towards a hydrogen economy is a multidimensional challenge, requiring an understanding of not only technical but also societal aspects.

Moreover, it is essential to recognize that hydrogen-based technologies set themselves apart from other energy technologies through their multi-stage acceptance criteria. This is because the idea of a hydrogen economy covers the entire energy supply chain, from production and transportation to storage and end use. While the existing literature provides valuable insights, there are areas like longitudinal studies, system perspective studies and cross-comparative studies that require more attention. By addressing these research gaps, we can develop a more comprehensive understanding of the field, which is crucial in advancing towards a sustainable, hydrogen-driven future.

From the literature review, the following research gaps were identified:

1. Limited temporal studies: While the evolution and growth of the hydrogen economy have been studied, there is a gap in studies that provide a comparative analysis between different time periods, especially concerning global development and stakeholders' perception.
2. Lack of system perspective studies: There is a lack of national studies evaluating public perception of hydrogen from a system perspective, which encompasses the entire hydrogen supply chain, including production, transportation, and distribution.
3. Lack of cross-comparative studies: Despite numerous national studies, there is a lack of comparative research exploring the regional differences and commonalities in the development of the hydrogen economy, including perceptions of its drivers and barriers.

Chapter 3 A Historical Analysis of Hydrogen Economy Research, Development, and Expectations, 1972 to 2020

3.1 Introduction

In recent years, researchers in science, and historians, have shown a keen interest in understanding the potential of various streams of technological development [63], [120], [121]. While historical analysis [122] and technology forecasting [123] are not new, they have been used more extensively to explore different energy scenarios or identify possible barriers and drivers in today's society. Thus, there is a demand for studies that can forecast a future emergent technology's progress based on earlier expectations [124], [125]. One of the key ideas leading to this type of research is the concept of hype.

The concept of 'hype' is widely used in mass media in a deliberate and exaggerated effort to attract people's interest [126]. Marketing practitioners recognize that hype generates attention and can influence diffusion patterns [127]. The Gartner Hype Cycle Model was developed based on this insight to track the development of technology versus its visibility. A hype cycle is a generally observed pattern characterized by strong and rapid increases, followed by subsequent decreases, in both societal attention to and expectations about a technology. The hype cycle model tracks the development of a technology as it progresses through successive stages of peak, disappointment, and recovery of expectations [127]. The hype cycles of technological innovation are recognized as an integral part of the history of technology and not something that only exists in the initial development stages. Based on this perspective, it is possible to explore the nonlinear progress of how technological innovation is intertwined with expectations created by different historical actors [128], [129].

Although the hype cycle model has gained substantial academic attention, case studies using the hype approach to explore technological transition have thus far remained limited. Studies that have used the hype approach are renewable energy [130], energy storage [131], and hybrid cars [132]. However, the hype cycle has not been used extensively to explore the development of the hydrogen economy. Presently, bibliometric analysis, literature review, and historical analysis have been widely used to analyze the development of the hydrogen economy.

3.1.1 Research Objectives

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

3.2 Methodology

To examine the development of the hydrogen economy from multiple perspectives, three sets of interconnected data are collected and analyzed: academic publications, media articles, and industrial projects. Figure 5 outlines the methodology used in this study.

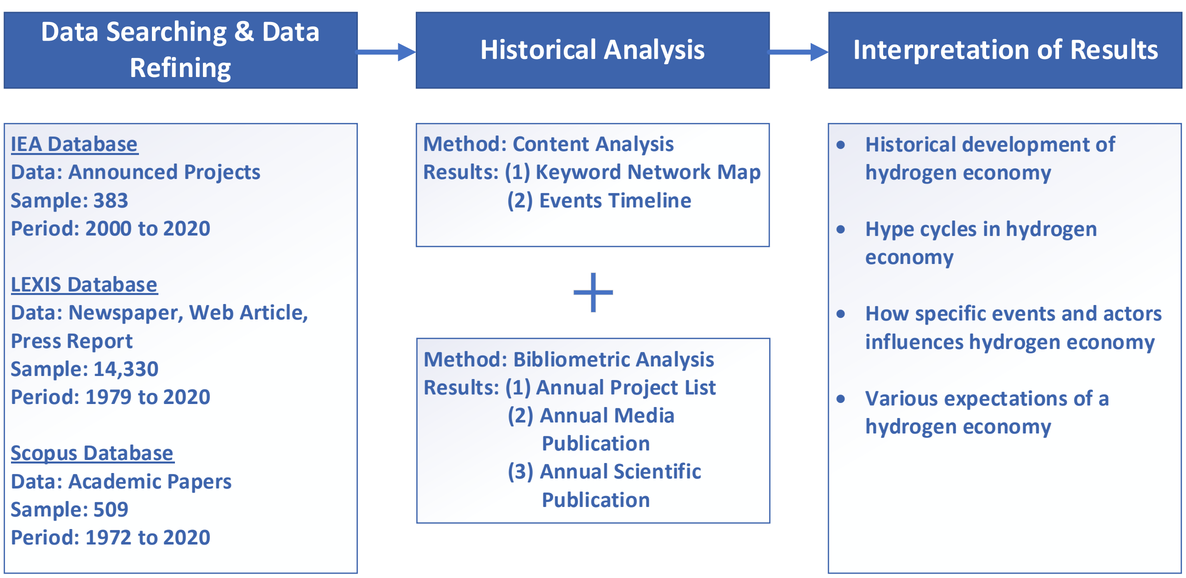

Figure 5: Research Methodology of Historical Analysis

To evaluate research trends in the scientific community, Elsevier's Scopus was selected for this study as it is one of the largest databases of peer-reviewed academic literature. Although some studies show better results are obtained by using more databases (Scopus, Web of Science, Google Scholar), a high percentage of Scopus results are also found in Web of Science and Google Scholar [59]. To gauge the interest of society, the LEXIS database was chosen as it covers a wide range of international media, such as newspapers, press releases, industry news, and web publications. Several publicly available databases include the European Union's Fuel Cells and Hydrogen Joint Undertaking Projects, the United States Department of Energy Hydrogen Program, and the IEA hydrogen database. However, only the IEA database encompasses worldwide projects, and the coverage period is the longest (since 2001). The IEA database consists of government and privately funded projects to implement hydrogen production. Thus, the IEA hydrogen database was selected to evaluate industry perspectives [133].

In this study, the search query is important to capture the longitudinal dynamics of the existing body of knowledge. For example, "hydrogen energy system" was used interchangeably with "hydrogen economy" in the earlier period of development of the concept, so it is important to identify and include search queries that have similar meanings to "hydrogen economy." The search queries for Scopus and LEXIS databases are documented in Table 12.

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

The historical analysis depends on making use of the existing body of knowledge. This task is increasingly challenging to manage, given the exponential growth rate of published literature over recent years. However, with large-scale digital databases and powerful computer processors, researchers have used data mining to discover new information or linkages across extensive collections of articles. Although this technique cannot replace human interpretation in complex tasks, it can be used to quickly identify research gaps or construct a research timeline by analyzing large volumes of information. At present, keyword co-occurrence analysis is one of the most used methods by researchers to identify emerging research themes [52], [54]. Keywords are represented by nodes, while the links represent the co-occurrence relationship between the keywords. The size of the nodes represents the number of times a keyword appeared in the collected studies. The association strength between the keywords defines the frequency of a pair of keywords co-occurring in multiple studies.

Many studies [121], [134] use an arbitrary number to adjust the keyword list based on appearance frequency, but this method may also cut off critical linkages between other keywords. To optimize the knowledge mapping visualization, keyword grouping is used to group related keyword clusters and reduce the total number of keywords. The keywords are grouped into a hierarchy system of topical and related specific keywords. For example, "natural disaster" is considered a topical keyword, while "tsunami" is a specific keyword. However, it is important not to group too many keywords under a topical group as this will lead to oversimplification of keywords and risk losing potentially useful information. This study conducted keyword co-occurrence analysis on Scopus case studies as author keywords, and Scopus index keywords could be readily retrieved. Generally, keyword co-occurrence mappings cover the study period, but the mapping can also be divided into regular time intervals. The mappings in this study are divided into decades (1972–1979, 1980–1989, etc.). This approach adds a chronological layer to the mapping and tracks the development of the hydrogen economy historically.

3.3 Results & Discussion

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

3.3.1 The History of Hydrogen Economy by Keyword Mapping

Keywords are scientific terms that represent a summary of academic studies. 2166 unique keywords were extracted from 509 studies in the Scopus Database from 1972 to 2019. After data cleaning, 1003 unique keywords were categorized into 125 specific keywords under 11 topical themes, Figure 43. In general, three development phases can be observed, a slow growth phase (1972–1979), a stagnant growth phase (1980–1999), and a rapid growth phase (2000–2019).

3.3.1.1 Slow Growth Phase (1972–1979)

During the slow growth period, 45 publications fitting with the scope of analysis were published in the 8 years, comprising 9% of the total analyzed publications. Hydrogen research only started to gain some recognition in the context of energy after the term "hydrogen economy" was coined by John Bockris in 1972. Before 1972, there was no official concept of the "hydrogen economy," and scientists were mainly focused on the practicality of hydrogen as a fuel. This is evident as the most central node is "hydrogen" instead of "hydrogen economy," as illustrated in Figure 6. The 1970s was a critical decade in the context of energy, in which the international energy crises (1973 oil crisis [135] and 1979 energy crisis [136]) started a search for more resilient energy systems, including options such as utilizing hydrogen. Hydrogen interest in this decade peaked in 1974 with the establishment of the International Energy Agency (IEA) and the International Association for Hydrogen Energy (IAHE). One of IEA's priorities was to respond to the global oil crisis by exploring alternative technologies such as hydrogen [137]. The golden age of nuclear power has widely been considered to span from the mid-1940s to the late 1970s before the Chernobyl Accident in 1986 [138]. In line with this, nuclear energy was widely considered as an option to produce abundant and cheap hydrogen in addition to electricity [139], [140]. In this decade, environmental concerns were not the main motivation for a hydrogen economy.

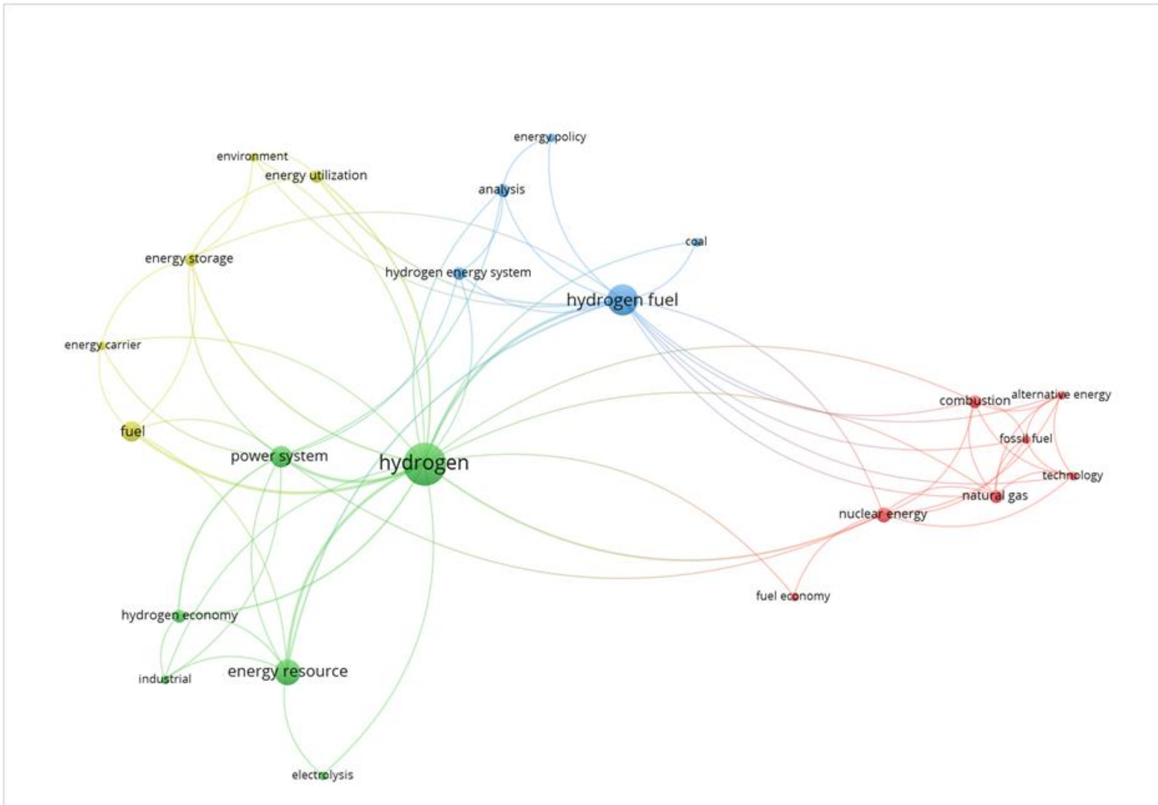

Figure 6: Keyword network map for 1972 to 1979

3.3.1.2 Stagnant Growth Phase (1980–1999)

During the slow growth period, 37 publications fitting within the scope of analysis were published across 20 years, comprising 7% of the total analyzed publications. As indicated in Figure 7 and Figure 8, although the number of publications decreased significantly, the network of keywords grew compared to Figure 6. The total number of papers and keywords for each period is documented in Table 13: Summary of keyword co-occurrence analysis. During the 1980s, hydrogen research branched into several new areas, including using hydrogen as storage and producing hydrogen from solar energy and other alternative energy [141]. In Figure 7, the interconnection between the keywords of “solar energy,” “hydrogen production,” “energy storage,” and “electrolysis” support this theory. The rising interest in cleaner energy may also be associated with the scientific community focusing on producing clean hydrogen from nonpolluting resources. However, during this decade, the low oil price hindered further development towards clean energy transition [142]. At the same time, the 1986 Chernobyl disaster reduced the attraction of the idea of production of hydrogen from nuclear energy.

Hydrogen research confronted a puzzling situation in the 1990s. Climate change gained enough attention to result in the United Nations Framework Convention on Climate Change (UNFCC) in 1992 [143] and subsequently the Kyoto Protocol in 1997 [144]. This can be associated with increasing keywords related to environmental concerns, as shown in Figure 8. The Kyoto Protocol had a significant impact on the development of clean energy, which also reinvigorated the vision of the hydrogen economy. Starting from 1998, the hydrogen economy publication trend accelerated, and 84% of publications were recorded after the signage of the Kyoto Protocol.

In 1983, Ballard Power Systems started investing in the development of fuel cells which later attracted Daimler Benz and Chrysler to develop the next generation of fuel cell vehicles [145]. In the following years, in the early 1990s, scientists managed to reduce the platinum in the fuel cell by one-tenth of its original amount and significantly reduce the cost of production [146]. However, the price of fossil-fuel-powered vehicles remained cheaper than fuel cell vehicles even with this major improvement.

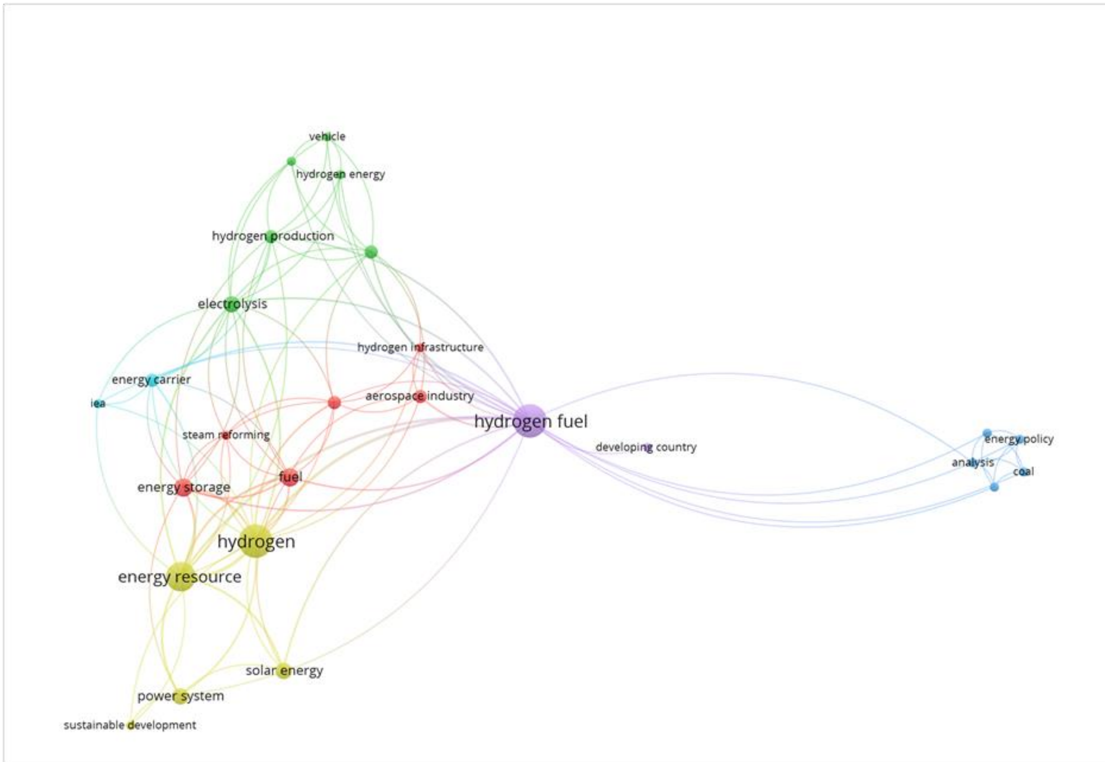

Figure 7: Keyword network map for 1980 to 1989

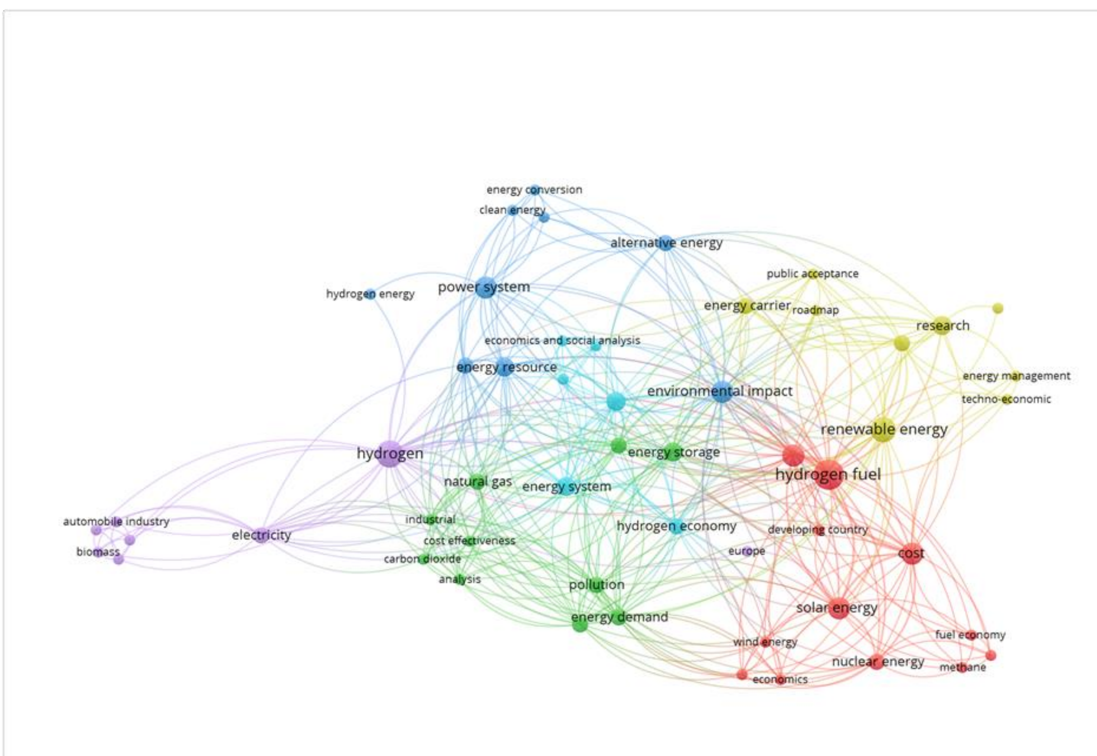

Figure 8: Keyword network map for 1990 to 1999

3.3.1.3 Rapid Growth Phase (2000–2019)

Compared to earlier decades, hydrogen research was more developed and integrated with the exponential growth of publications and the emergence of new keywords and clusters. 430 publications were published in the last 20 year period, which constitutes 83% of the total publications. This sudden publication burst is also associated with the information era since the early 2000s [147]. Our knowledge library has been converted to a digital format which also streamlined the publication process to enable faster review and publication, as well as easier archiving and freer keyword selection.

The 2000s and 2010s have been considered the renewable energy era as renewable energy and related technologies grew significantly [148]. The annual global investment increased 10 times from 2003 to 2012. By 2012, renewable energy had overtaken fossil fuel and nuclear energy in global yearly investment [149], [150]. As renewables grow, hydrogen became seen as an option to act as storage to solve the intermittency of renewables. The synergy between hydrogen and renewable energy can address the growing need for power system flexibility and clean energy production [128], [149]. Hydrogen production with fossil fuels was still seen as relevant, but with CCS technology considered more important for carbon mitigation, particularly with a number of major hydrogen programs having a strong coal-based production focus [151].

Concerns over imported oil supply security have been looming ever since the first oil crisis, but the 11 September 2001 attack intensified this concern. As a means of diversifying the energy mix, the United States and the European Union launched a collaborative effort to accelerate the development of the hydrogen economy in 2003 and ultimately may have reenergized the interest in hydrogen-related research since then [152].

Starting in the mid-2000s, the demand for lithium increased significantly as a critical component for batteries in electronic devices and electric vehicles. In that period, the lithium-ion battery (LIB) price also dramatically decreased [153]. In addition, from 2011 to 2017, battery density has been improving at a rate of 7.5% a year, meaning battery packs will be smaller and last longer [154]. Hydrogen and LIB are regarded as competitors in many areas, so the advancement of LIB contributed to the reduction in interest in hydrogen technologies.

Additional causes for the 2010 publication decline could be linked to a lag effect of the 2008 global financial crisis (reduced research funding, etc.) [155]. The Fukushima accident in 2011 also decreased the public acceptance of nuclear energy, and nuclear relevant keywords were nowhere to be found. The ratification of the Paris Agreement in 2016 may have contributed to the renewed interest in hydrogen energy in subsequent years [39]. In addition, more keywords associated with climate change have increased due to climate concerns of the previous decade. The establishment of the Hydrogen Council (HC) in 2017, which unites the world's biggest oil companies and industrial players, has revigorated the hydrogen economy by drafting blueprints to enable the transition to a future hydrogen economy [156], [157]. To realize the hydrogen economy transition, research is more focused on drafting policy and building infrastructure to facilitate this transition. As a result, "policy," "roadmap," and "modeling" keywords have appeared more frequently. This was also when "hydrogen economy" became the central of node, as shown in Figure 9 and Figure 10. The uniqueness of the current hydrogen hype is the broadness of its base compared to the previous hype cycle when the discussion was focused on a specific area of hydrogen technologies.

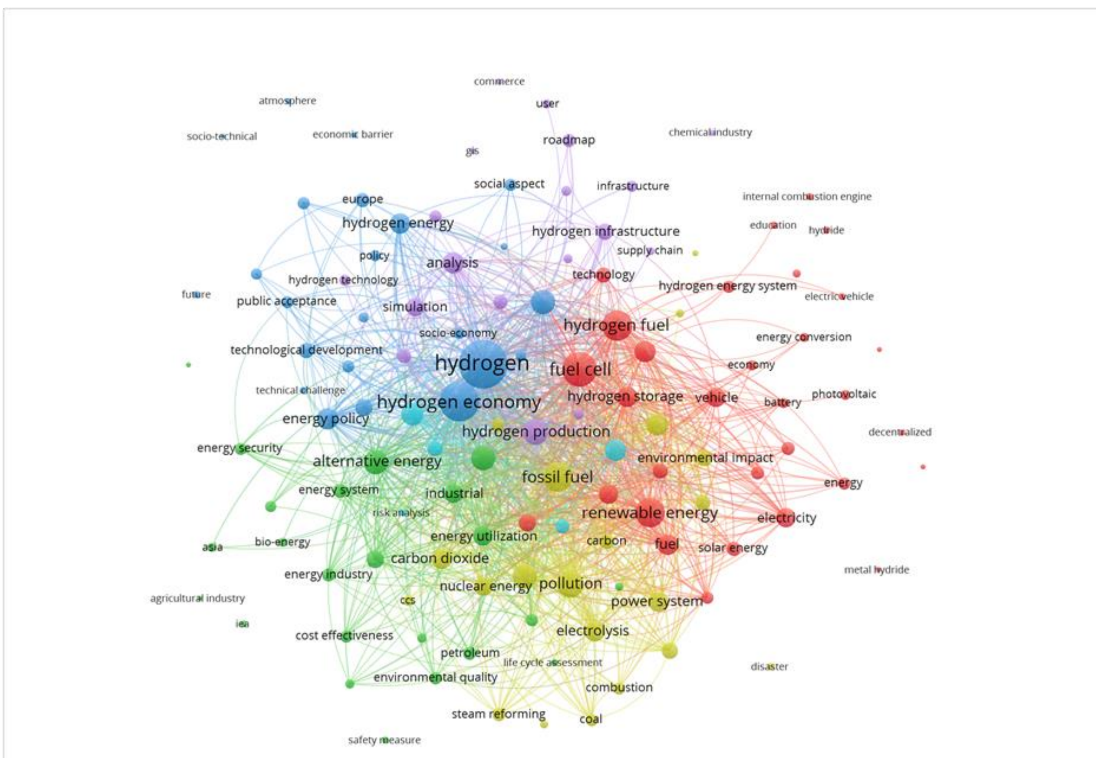

Figure 9: Keyword network map for 2000 to 2009

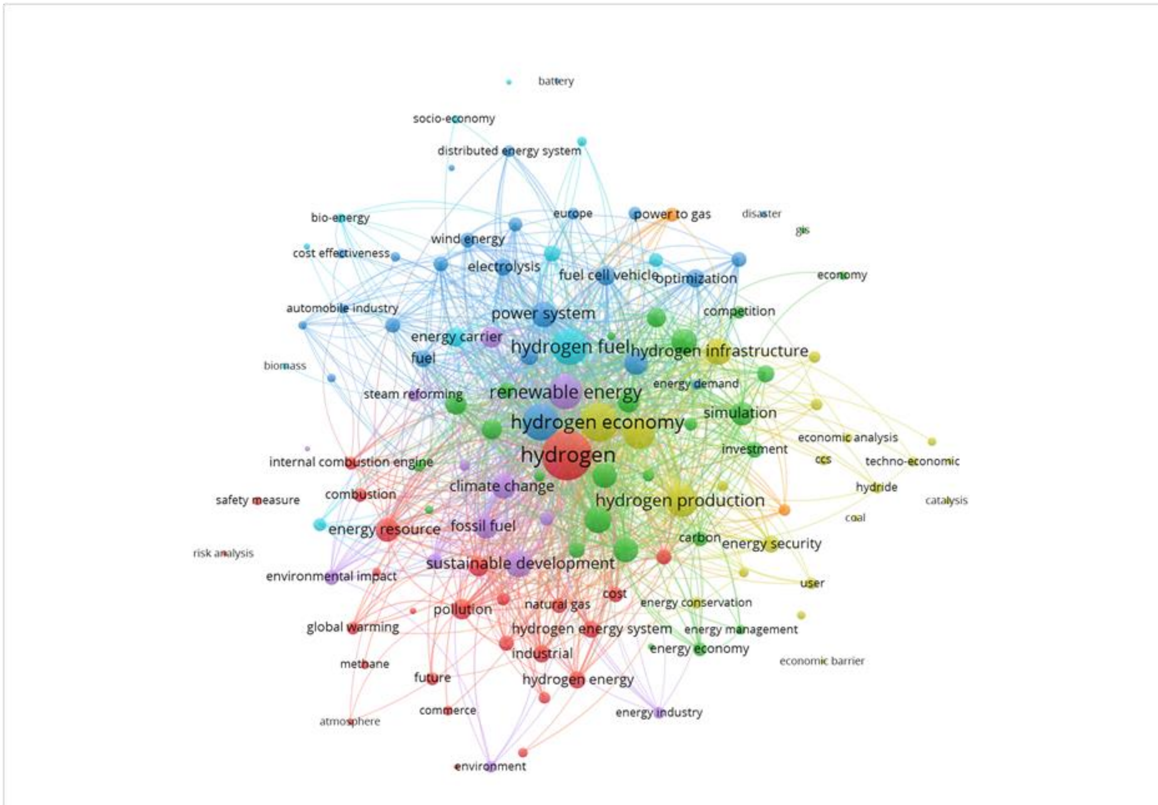

Figure 10: Keyword network map for 2010 to 2019

3.3.2 Historic Interest in Hydrogen Economy

The analysis results, in the form of annual academic publications, mass media articles, and hydrogen-related projects, were normalized and then mapped chronologically against specific potentially relevant events to represent historical interest in the hydrogen economy, as shown in Figure 11. The three data sets were normalized across the range of occurrences, with the year of maximum occurrence set to 1 and minimum occurrence set to 0 to compare them on the same scale. From a quantitative perspective, interest in the hydrogen economy has significantly progressed over the past five decades based on the growing numbers of academic publications, media coverage, and projects. However, cyclical patterns have also been observed over the years, hereby referred to as the hype cycle. The upward trend represents an increase in interest toward a hydrogen economy, while the downward trend represents a decrease in interest.

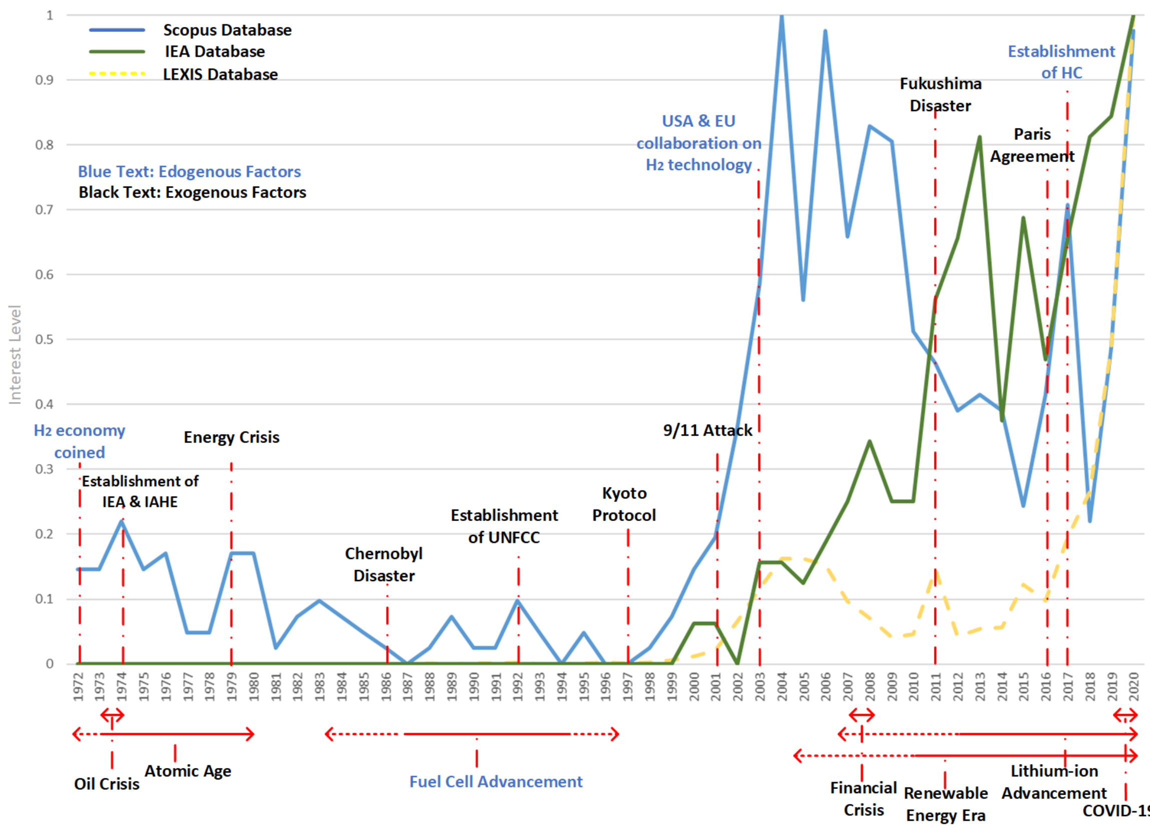

Figure 11: Normalized annual publications in selected literature and databases, with relevant events highlighted (no causality proven between events and interest)

Early-stage innovations or technologies face challenges and barriers, but it may be argued that the hype cycles are more apparent in hydrogen-related technologies. Figure 12a shows the normalized annual journal publications of fuel cell vehicles (FCV) and electric vehicles (EV) retrieved from the SCOPUS database, while Figure 12b shows the normalized annual articles on fuel cell vehicles and electric vehicles retrieved from the LEXIS Database. By comparing the trends for FCV and EV, it is apparent that the FCV graph shows more peaks and troughs, despite an overall increasing trend across the period. We consider this as an indication of hype cycles, in which attention to hydrogen technologies peaks and wanes. On the other hand, EV progress and attention has been progressing at a much steadier rate. Although in part this may have some correspondence with the total number of publications regarding each topic – EVs have more than 20 times the overall number of publications of FCV, so it is possible that fluctuations are less obvious on an annual, normalized scale. The difference may be that while EV have progressively made their way into the market, with improvements in range and accessibility of infrastructure, as well as decreases in cost, FCV have offered a seemingly attractive alternative but have not delivered the foreseen benefits or uptake. In the academic literature, such trends can of course follow trends in funding, which may be directly or indirectly related to societal uptake of a given technology.

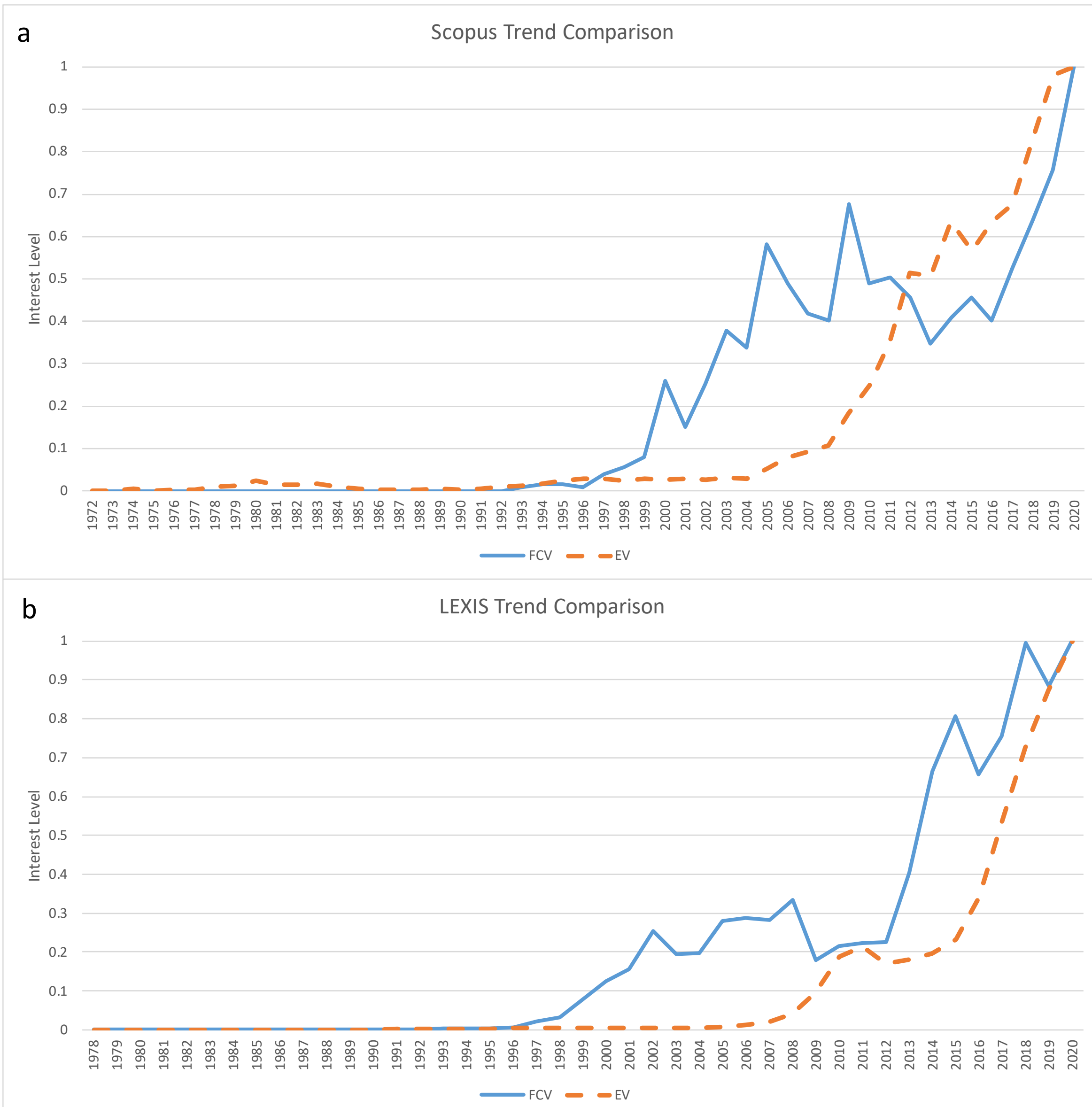

Figure 12: Trend Comparison between FCV & EV (a) Normalized annual publications from SCOPUS (Highest Publication at FY2020, FCV: 127, EV: 3718) (b) Normalized annual publications from LEXIS (Highest Publication at FY2020, FCEV:1566, EV: 58598)

The historical interest in the hydrogen economy as an emergent concept has followed the trend of the hype cycle. The hype cycle represents a relationship between technology maturity and its visibility [158]. In academia, scholars refer to the concept of hype as a rapid increase and subsequent decrease of societal interest in transition studies [130], [131]. The hype cycle can be associated with endogenous and exogenous factors acted upon by individuals, societal groups, industries, and organizations. Furthermore, factors can be divided into the trigger and long-term events. It is difficult to precisely identify the starting point of long-term events as its development is a gradual process. Hence, the development phase is marked by dotted lines, while a solid line marks the expansion era as illustrated in Figure 11.

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

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

3.3.3 The Roles of Actors in Energy Transition

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

A sustainable energy transition requires technological innovations and the collaboration and participation of actors at different levels of society [159]. By applying the societal typology in Fischer and Newig's review [160], four main actors in different societal realms are identified: policymakers, industry, academia, and members of society.

The energy sector is key in leading the way to a zero-emission society with technological breakthroughs and rapid cost reduction. However, it could be faster if driven by institutional frameworks. By setting ambitious targets and goals, more investors, scientists, and cities are challenged to advance. At the institutional level, policymakers govern the energy transition through regulatory frameworks and policy solutions [161]. It has been argued that initiatives toward transitions mainly depend on what society demands. Still, policymakers can promote the reinforcement of a sustainable transition in institutional frameworks which can provide the necessary guidelines to foster the development and diffusion of technological innovations.

At the intermediate level, industrial sectors such as steelmaking, chemical, and aluminium manufacturing are the main contributors to carbon emissions due to their inherent requirement for large amounts of energy. Energy-intensive sectors that are unable to decarbonize via direct electrification are considering the prospect of using hydrogen as a more carbon-neutral alternative. The required technologies may exist but are not always the most cost-effective choice, and there is often significant inertia against change due to the invested capital and incumbency. Thus, policymakers and industry must work together to create a market mechanism based on institutional policies to counter competitive disadvantages and simultaneously deliver necessary changes in carbon emissions from the industrial sector [162].

Academia has a mediating role by providing and distributing the necessary knowledge, information, and technologies between institutions, industry, and society [163]. For example, researchers across disciplines can share their expertise with policymakers to understand how science can help design better policies to tackle environmental pollution, improve energy efficiency, and support the transition to a zero-emission society, while at the same time educating society on the importance of solving environmental and energy issues.

At the societal level, citizens are empowered when they play an active role in the discussions, decision-making, and implementation of projects or policies affecting them [160]. For example, the participation of society in the development of institutional frameworks via functions such as reviewing and providing feedback on current guidelines.

In energy transition, actors can either be supporting or opposing forces relative to the transition under consideration. There are always forces that support or oppose the development of the hydrogen economy. For instance, while hydrogen supporting policies and international commitments have a positive effect, lobbying pressure from traditional energy companies wanting to maintain the status quo has a negative effect. The adoption of hydrogen technologies will be supported by some [101], [164], while others will criticize the reliability of hydrogen-based technology in favor of competing technologies such as batteries [165]. Another example is industry actors, whose position depends on their business agenda. By evaluating each technology's strengths and weaknesses, companies can either diversify their business strategies with new technological developments or stick with established technologies to oppose development. Understanding actors' roles and agendas can help classify them as supporting or opposing forces. The power balance between the two coalitions can influence decisions, investments, processes in the ongoing energy transition [166].

Building on the above, a conceptual framework has been adapted from [130] to describe the power balance between competing actors and their influences, as shown in Figure 13. Actors in each coalition are engaged in narrative work and share their respective views, disseminating information based on their expectations for a hydrogen economy. Kriechbaum et al. [130] suggested that hypes cycles are driven by such narrative works and exemplified by discursive struggles between competing views on the respective technology. Specific events create space and allow supporters and opposers to share their expectations. Recent socio-technical transition studies have emphasized the role of specific events in hype cycles` emergence [130], [131]. Hype cycles can be influenced by trigger events and long-term events over a more extended period, which may be seem to some extent in Figure 11. Endogenous events, such as technological breakthroughs and supporting policies, have a positive impact. The changes in the wider socio-technical economic content, characterized as exogenous events, play important roles too. For instance, advancement in competing technologies, financial crises, and changes in society's sociological and economic interest.

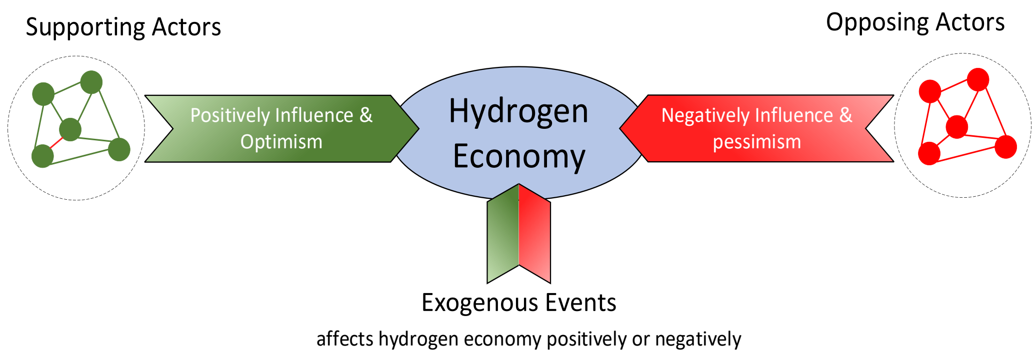

Figure 13: Conceptual framework of the influences towards hydrogen economy

3.3.4 Expectations of the Hydrogen Economy

The hydrogen economy has attracted the attention of many and fostered great expectations. However, it is important to note that each actor operates in different societal realms with their own agendas or preferences, which may positively or negatively influence the development of the hydrogen economy. As in the parable of blind men and an elephant, many people interpret the hydrogen economy differently. However, each actor's different yet overlapping expectations have created somewhat of a shared concept of hydrogen economy which is flexibly interpreted as to what a future hydrogen economy may look like. This study draws on the work of Borup et al. [129], Van Lente [167] and Brown and Michael [124] to describe expectations as future-oriented abstractions that fuel the creation of opportunities and hopes, technological developments, economic growth, and also some kind of shared concept or image of what is to be expected.

A shared concept is vital to create common ground for emerging technology and innovation to develop freely [128]. Common ground will allow actors with different agendas to work and collaborate. Expectations play an important role in mobilizing resources at various levels, for example, at the institutional level by national policy regulation, at the intermediate level by collaborative efforts between institutions, and down to the individual level in the work of an engineer or researcher. As such, expectations can be seen as a bridge to mediate across different actors at different levels of societal realms. Historically, expectations tend to change over time, especially over a longer timeframe, in response to new conditions or issues, evolving social ideology, and the advancement of technology. As a result, hype cycles are a frequent occurrence due to the dynamic structure of expectations. As shown in Table 8, the difference in interpretation based on each actor's historical narrative and motives are an example of such perspectives, described further below on the basis of reviewed literature.

Table 8: Summary of actors and their interest in hydrogen economy

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

In hydrogen production, there has been a division between methods that use fossil fuels and those that use renewable energy. Among the most prominent advocates of the hydrogen economy are the oil and gas industry companies, which have in some cases rebranded themselves as energy companies. As environmental concerns increase, energy companies are trying to determine ways to extract value from their stranded assets in the energy space, leading to an interest in blue hydrogen. Almost all energy companies have announced plans or roadmaps utilizing blue hydrogen as an intermediate phase before transitioning to green hydrogen [168], [169]. Blue hydrogen is hydrogen produced from fossil carbon fuels coupled with carbon capture and storage technology. In contrast, green hydrogen is hydrogen produced by electrolysis from renewable sources by breaking down water molecules into oxygen and hydrogen. The image of carbon-free energy is usually associated with green hydrogen. However, some energy companies are suggesting a transitioning period where hydrogen is derived from fossil fuels, then switching to blue hydrogen, and finally to green hydrogen as electrolyzer technology becomes cost competitive. This initiative is backed by fossil fuel lobby groups and some of the world's largest oil and gas companies. However, this transitioning phase poses a threat to green hydrogen production as the high investment cost of blue hydrogen infrastructures will result in a phenomenon called technology lock-in. Large-scale projects require many years and funding to be built, and they are designed to last for decades. The fossil fuel lobby group does not often mention this but is constantly argued by an environmental group and green hydrogen advocates [170], [171]. Most notably, Corporate Europe Observatory, in a 2020 report, criticized the fossil fuel lobby group for undermining the true goal of the hydrogen economy, which is hydrogen produced by clean energy sources [172].

On the other end of the spectrum, environmental groups and like-minded people believe that blue hydrogen is delaying the transition, and green hydrogen should be the only way forward [99,100]. For green hydrogen to move from commercialization to dominance, investment and effort should be started now instead of later. This is to achieve economy of scale and bring down the cost of manufacturing electrolyzers, which in turn lower the cost of green hydrogen, just as how Tesla was able to revolutionize electric vehicles in the 2010s by focusing on the development of lithium-ion batteries [175], [176].

Amid the blue hydrogen and green hydrogen debate, financial institutes have realized the opportunity to combine economic growth with environmentally friendly technologies and adopted hydrogen technology in their business ventures. Many of the world's biggest companies have shifted their focus to capitalize on this untapped market [5], [177], [178].

Energy companies envisioned hydrogen economies driven by natural gas [169], [179], [180], environmentalists envisioned hydrogen economies to counter climate challenges [150], [181], and economists envisioned hydrogen economies as new business opportunities [182], [183]. However, expectations are created in different contexts such as different settings, actors, points in history, and locations but may be connected in various ways.

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

Despite the difference in interpretations, each actor is advancing on believing that the hydrogen economy will offer technological solutions to environmental and economic issues. This same message was repeated among different actors and passed on to society, creating a hydrogen hype [24], [146]. However, more often than not, this utopian image of a hydrogen economy was being communicated without considering the complex history or technological barriers. There are major mismatches between the present situation surrounding the hydrogen economy and previously announced milestones that are still far from being reached [114]. Articles focus on how hydrogen technology will fit into future energy systems rather than how to roll out the technology realistically. This optimistic view created an unrealistic and unbiased expectation which will subsequently lead to the downfall of the hydrogen hype.

As evident in Figure 11, various endogenous and exogenous factors have influenced the development of the hydrogen economy and created hype at different points in time. Each hype comes with the expectations that the hydrogen economy is on the verge of a breakthrough and would be the ultimate solution for climate change. Despite the previous false start, advocates still believe in the utopian image of the hydrogen economy. Journalists kept reporting hydrogen-related articles, politicians adopted hydrogen technology as their environmentally friendly policies, publications on hydrogen were growing, and industry unveiled prototypes at every exhibition. This blinded enthusiasm goes together with the belief that, sooner or later, everything will fall into places like breakthrough or mass production. With each new hype cycle, actors deny or forget the downfall of previous hype and discuss the last development to fit into a linear narrative of progress. The lack of sense of history can be observed in mass media or hydrogen roadmaps. Most media ignore the complicated history and report about the next big thing while roadmaps are being rebranded with new targets with every release. This is contributed mainly by our growing internet library, in which history has been buried.

However, it is important to note that transition is often nonlinear progress, and previous hypes are recognized as an integral part of history. Although roadmap targets are mostly overshot, technological progress is still being made. The efficiency of both fuel cells and electrolyzers are increasing, while the costs are decreasing. Technologists who advocate upcoming technology tend to overestimate performance and cost targets while underestimating actual progress. In the past, society was pessimistic about the growth of renewable energy as it failed to deliver its promises due to inflated expectations [148]. Now, renewable energy, especially solar and wind, has grown rapidly, and most renewable energy technologies exceed their targeted cost and performance [184]. The hydrogen economy and its technologies face similar obstacles as its predecessors before global acceptance can be gained.

3.4 Conclusion

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

The past is linked to the present by a continuous chain of events [115], [185]. By understanding the past narratives of the hydrogen economy through the theoretical concept of actor's roles in transition and sociology of expectations, researchers and policymakers alike can better work towards a common hydrogen economy. In a 2021 report [1], IEA noted that there had been many false starts on the emergence of a global hydrogen economy in the past; and believe the current wave of interest could be different, with global efforts to reduce carbon emissions and transition to a cleaner future. Despite the optimistic outlook, it is yet to be seen whether the current wave of interest is another period of hype or, finally, the emergence of an operating hydrogen economy. Thus, assessing the current perspectives of society on a hydrogen economy is important to understanding social support, align our expectations of the hydrogen economy, and track our current progress toward a future hydrogen economy. Further work to investigate this through community and expert surveys will be discussed in Chapter 4 and 5.

3.4.1 Limitations & Future Work

This study encountered several limitations that should be considered in future studies. The keyword co-occurrence analysis relied on article keywords (either from authors or Scopus) to historically map the development of hydrogen economy due to analyzing a large amount of data. As a result, the analysis reflects how authors and Scopus summarized the articles using keywords. The absence of some keywords may reflect a lack of research on that topic, but it could also reflect relevant topics caused by coordination problems in assigning suitable keywords. In addition, the social aspects of the hydrogen economy need to be examined to address the current understanding gap between different realms of society and people's preferences and perceptions towards the acceptance of using hydrogen as part of their daily lives. A sustainable transition to a hydrogen economy will require governance structures that are both participatory and inclusive, which empower all members of society to become full stakeholders in sharing its benefits. This study uses academic publications, media articles, and industrial projects to examine the development of the hydrogen economy. However, patent data was omitted in this study due to accessibility issues, as many relevant patents are not publicly available. In addition, patent data are filed in individual countries, therefore it is challenging to compile and analyze them in a manner that accurately represents global trends and developments.

Chapter 4 Evaluating the Attitudes of Japanese Society Towards the Hydrogen Economy: A Comparative Study of Recent and Past Community Surveys

4.1 Introduction

The hydrogen economy refers to a vision of utilizing hydrogen as a transition pathway to an equitable energy system that is clean, low carbon-intensive, and beneficial to society. Hydrogen is an energy carrier that can be produced by a variety of energy resources and supports a multitude of end-use applications, including energy storage, transportation fuel, industrial processes, and more. Historically, the hydrogen economy has attracted the attention of many and resulted in multiple surges of interest over the years [114]. The hydrogen economy transition is dynamic and consists of economic, technological, and social structures that are constantly evolving. This transition is affected by endogenous factors by stakeholders with different agendas and exogenous factors outside of a hydrogen economy's system boundary. The diversity of hydrogen and its potential roles, as well as the ubiquitous application as an energy solution allows people to interpret it based on their agendas, resulting in competing interpretations of what a future hydrogen economy may look like [112]. This has created a gap between the public and scientific community understanding of the status of a hydrogen economy and raised false expectations in the past [1]. It is widely accepted in socio-economics that the success of emerging technology depends to a great extent on public acceptance [68], [75]. Emerging technologies such as hydrogen technology have received increased general coverage through the media [48], but public perception and acceptance are still relatively unclear [86].

4.1.1 Research Objective

The implementation of an operational hydrogen economy will require both the technical infrastructure and public support. Assessing society's acceptance of a hydrogen economy is important to understanding public support and ultimately avoiding unwillingness for hydrogen technology and infrastructure deployment. However, most of the survey-based studies on public perception or acceptance tend to focus on hydrogen end-use applications such as fuel cell vehicles and fail to address hydrogen from a system perspective [83], [96]. Hydrogen is an energy carrier, which needs to be produced, stored, transported, and distributed in an energy network [1]. Public perception and acceptance may be impacted by each process in the hydrogen supply chain, as there are different methods to produce and store hydrogen. There is however, a lack of national studies evaluating public perception and acceptance of hydrogen from a system perspective. Within this context, this study aims to analyse the current attitudes of Japanese society towards the realization of a hydrogen economy through a community survey and compare the results from previous surveys in 2015 [86], 2009 [85], and 2008 [84]. The questionnaire survey is designed to assess the public's perception, knowledge, and acceptance of hydrogen as an energy carrier, hydrogen infrastructure, and fuel cell technologies in Japan, as well as their personal values. This community survey is part of a parallel study (Chapter 5) with an expert panel survey that aims to clarify the different yet overlapping interpretations of hydrogen economy among different groups of society, mainly academic, industry, government, and the general public. It is crucial to understand the various interpretations of society and bring them together to exploit the diversity of hydrogen fully.

4.2 Methodology

This study uses a questionnaire survey for data collection. Surveys are an effective and simple method to gather descriptive data about public opinion, especially at the individual level. If the proper sample techniques are used, they can offer a general assessment of the population under study. Based on an earlier social acceptance study on hydrogen [67], a theoretical model was adapted to guide the formulation of the survey questions. The following model in Figure 14 was designed to evaluate and visualize various aspects that influence an individual's opinions toward the acceptance of a hydrogen economy. The three aspects are described as follow:

a. Knowledge on the Hydrogen Economy

   The literature review has indicated the discussion of hydrogen is still novel among the public audience. The level of knowledge is a good indicator to measure public understanding of hydrogen as individual opinion may be vulnerable to media hype reporting when access to hydrogen related knowledge is still limited. In addition, there are multiple interpretations or configurations of a possible hydrogen economy [112]. Each of these different hydrogen futures are being explored by different hydrogen supporters with their own agendas, characterized by different technology configuration, economic feasibility, and environmental sustainability. The different yet overlapping image of hydrogen economy is still a topic of substantial discussion and disagreement among experts in the field and a consensus has not been reached [186]. This raises the questions on how to inform the public on the innate complexity of this socio-technical transition.

b. Value

Personal values represent individual beliefs that serve as a guide in everyday life, motivate actions, decision making and ultimately in improving the quality of life [187]. Every individual holds various values with varying degrees of priority. As such, individuals with a stronger sense of environmental value (for example) would be expected to play a more active role in solving climate issues relative to those without [188].

c. Perception of Hydrogen Economy

The nuances of “Hydrogen Economy” are debatable. Hydrogen is typically regarded as an energy carrier, not an energy source because it needs to be produced, stored, and distributed to the end-user, similar to electricity [1]. Public perception and acceptance may be impacted by each process in the hydrogen supply chain, as there are different methods to produce and store hydrogen. Fossil fuels, renewable energy sources, or nuclear energy can all be used to make hydrogen. Given that each production method has advantages and disadvantages, will people accept them all equally? Similar questions can be made about various phases of the hydrogen supply chain. Therefore, a specific image must be established to influence the acceptance of hydrogen in daily life. The association of hydrogen with everyday life can serve as an indicator of how the public perceives the issues with the technology [96]

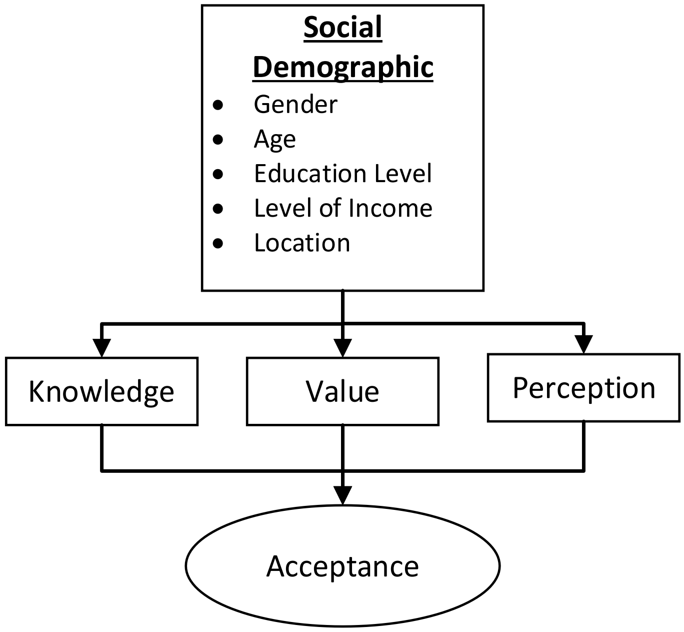

Figure 14: Theoretical Model of Public Acceptance of Hydrogen

The current study was conducted from a social-economic perspective rather than a technical-economic focus. The questions and structure of the survey were designed to allow comparison with a previous survey conducted in 2015 [86], using the same key questions in the questionnaire but also adapted to the specific objectives of the current study. In total, 23 closed-ended questions were formulated under four main aspects: (i) knowledge of hydrogen technology and various environmental policy; (ii) personal values and energy concerns; (iii) perception of hydrogen economy; and (iv) acceptance towards the establishment of hydrogen infrastructure in the community. In addition, social-demographic variables were included in determining the general characteristic of respondents and influences towards acceptance of hydrogen. Respondents were asked questions regarding their age, living location, educational background, and personal income.

The survey was conducted in March 2022 using an internet-based survey, with respondents being panelists of a Japanese marketing research company. The respondents were selected using a stratified random sampling method to ensure our results were representative of the Japanese population. As shown in Figure 15, A total of 2880 respondents were proportionally selected from the eight administrative regions of Japan based on Japan's 2020 population census [189].

Region	Allocation (%)
Hokkaido	4
Tohoku	6
Kanto	37
Chubu	16
Kansai	18
Chugoku	5
Shikoku	3
Kyushu	11

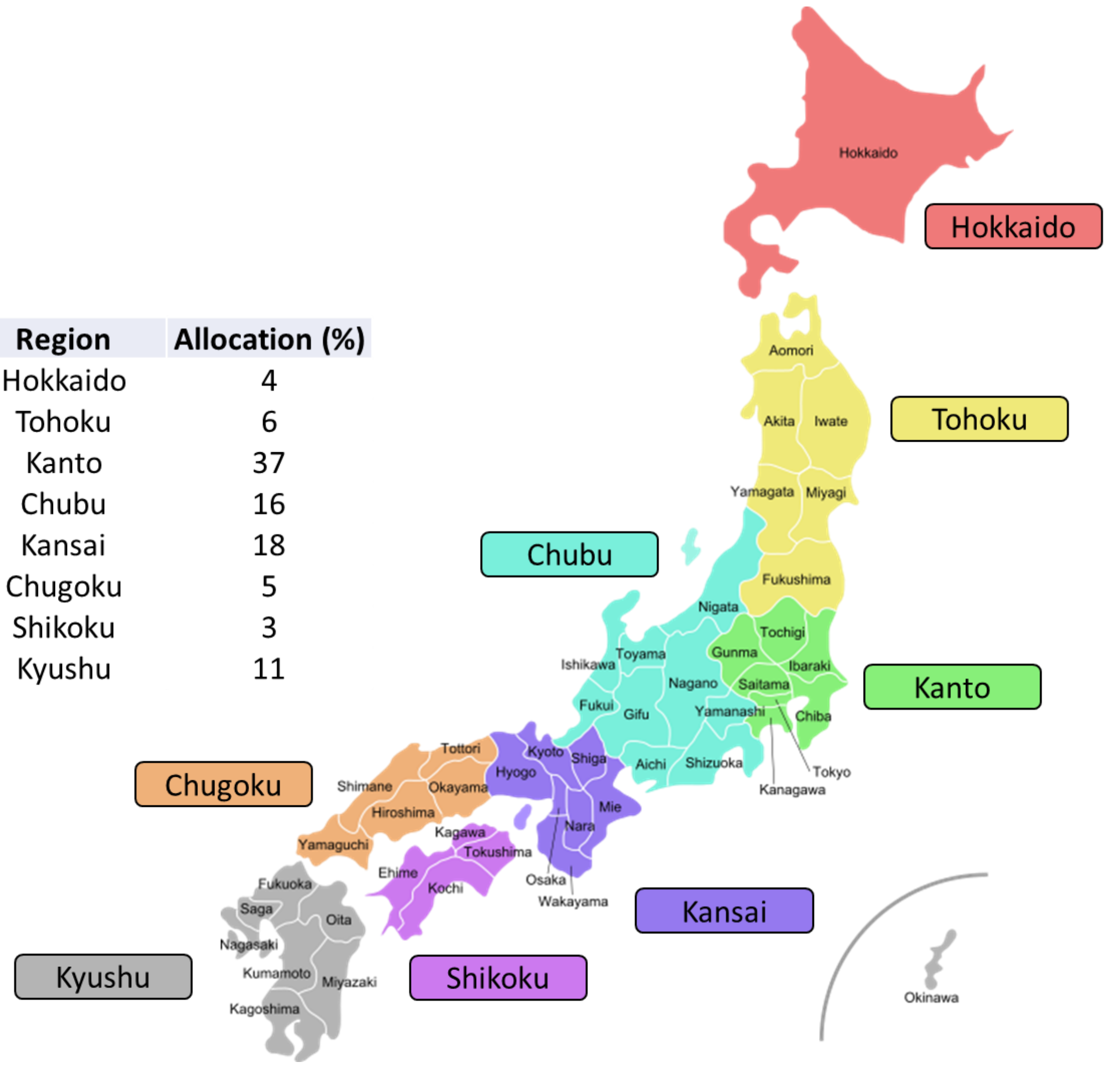

Figure 15: Eight administrative regions of Japan with respondents' allocation

The average age of the respondents was 42.8, and the majority of respondents had completed an undergraduate education (n=1071). One of the key differences between online surveys and traditional surveys is that online surveys may have a sample-biased towards younger sample populations [190]. In the present case, the traditional surveys conducted in 2008 and 2009 had an average age of respondents of 49.0 and 48.1, while the online surveys conducted in 2015 and 2022 had an average age of respondents of 45.4 and 42.8 respectively. Table 9 summarizes the social demographics of respondents.

Table 9: Social Demographics of Survey Respondents conducted in March 2022

Demographic of respondents (N=2880)	
Age Distribution (%)	
18-29	14.7
30-39	22.8
40-49	30.0
50-59	29.7
60	2.8
Regional Distribution (%)	
Hokkaido	3.5
Tohoku	6.5
Kanto	35.1
Chubu	16.3
Kansai	18.1
Chugoku	6.6
Shikoku	3.4
Kyushu	10.5
Education (%)	
Middle School	2.5
High School	29.8
Vocational School	15.6
Junior College School	10.4
Undergraduate School	37.2
Graduate School	3.8
Others	0.7
Personal Income (millions yen, %)	
0-2	36.0
2-4	21.5
4-6	13.3
6-8	8.2
8-10	4.4
Above 10	3.4
Unknown	13.2

4.3 Results & Discussion

The following section presents the descriptive analysis of the survey results and their implications under four key aspects: knowledge of hydrogen technology and various environmental policies; personal values and energy concerns; perception of hydrogen economy; and, acceptance towards the establishment of hydrogen infrastructure in the community. The current survey results are mainly compared with 2015 but also with surveys from 2008 and 2009 when applicable. The basic data implementation and the sample characteristics of all surveys are shown in Table 10.

Table 10: Basic data implementation and sample characteristics of survey

	2008	**2009**	**2015**	**2022**
Survey Period	Feb 2008	Oct 2009	Mar 2015	Mar 2022
Survey Area	Japan	Tokyo	Japan	Japan
Survey Method	Traditional (random walk)	Traditional (random walk)	Online	Online
Sampling Method	Two stage stratified sampling	Stratified sampling	Stratified sampling	Stratified sampling
Sample Size	1188	800	3133	2880
Average age	49.0	48.1	45.4	42.8
Average years of education	13.1	13.4	14.1	13.9
Percentage of female	51.0	50.3	45.4	55.1

4.3.1 Knowledge

A series of questions were asked to assess the public knowledge of various energy resources & technologies, hydrogen technologies, and environmental policies. The 2022 survey used a four-point likert scale comprising of "I know it well", "I know it fairly well", "I have heard of it", and "I have never heard of it". However, to facilitate comparison with the results from previous years, the scale was converted into a three-point scale by combining the options "I know it well" and "I know it fairly well" into a single option labeled "I know it". As a result, the final three-point scale included the options "I know it", "I have heard of it", and "I have never heard of it".

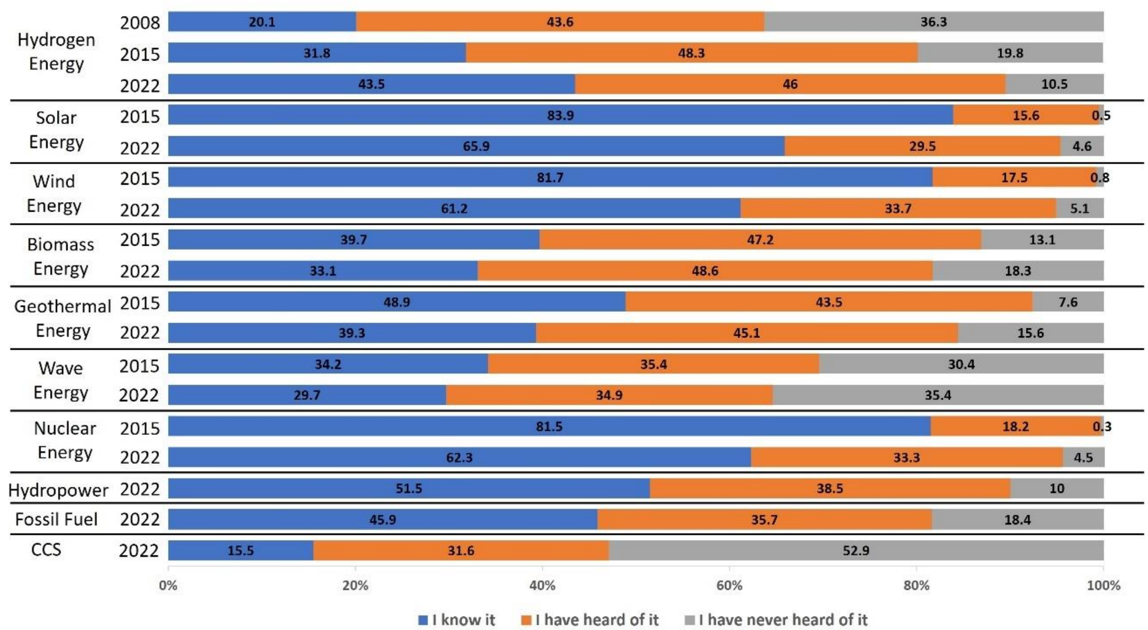

Figure 16: Self-reported knowledge of various energy resources & technologies

Figure 16 shows the results regarding the self-reported knowledge of various energy resources and technologies within the Japanese community. In 2022, self-reported knowledge of hydrogen was high, with 46% of respondents saying they had heard of hydrogen energy and 43.5% of respondents saying they knew the topic well. Additionally, the results comparison reveals that from 2008 to 2015 to 2022, public knowledge of hydrogen energy increased. It is noteworthy to highlight that public knowledge of hydrogen energy is comparable to that of hydropower, a well-known renewable energy. But compared to more popular types of energy like solar, wind, and nuclear, knowledge of hydrogen energy is lower. Geothermal and biomass energy are less well-known than solar and wind energy. Compared to biomass and geothermal energy, solar and wind energy are widely reported in mass media.

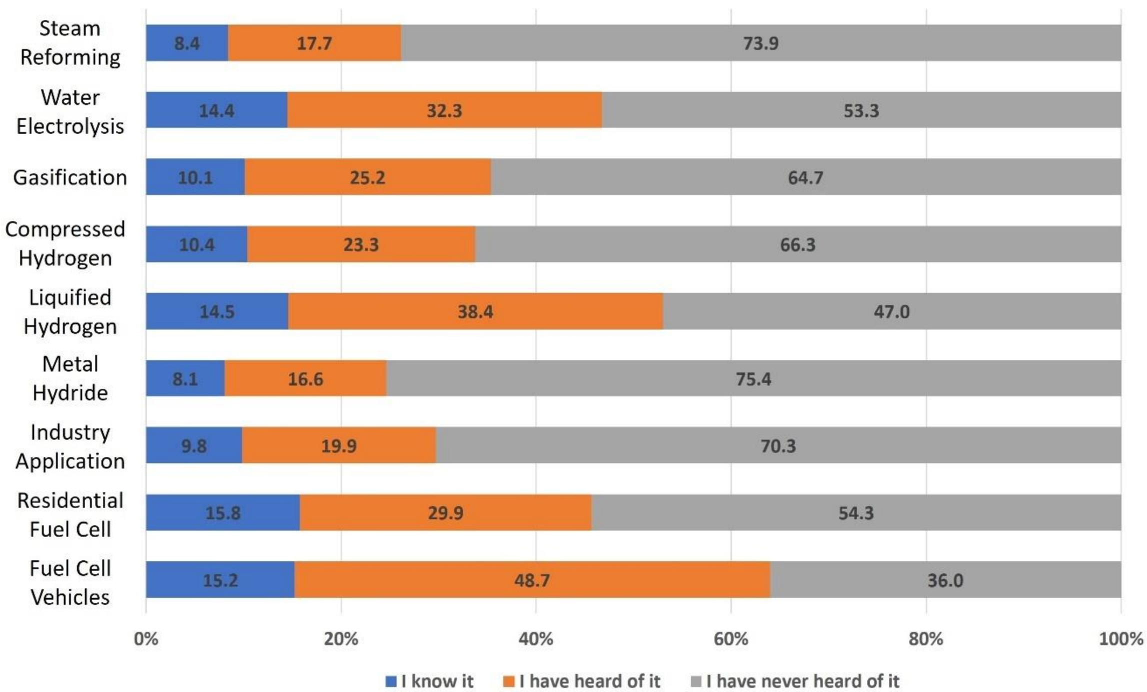

Figure 17: Self-reported knowledge of various hydrogen-based technologies

The prior experiences that people have had with a specific new technology play a significant role in how they perceive it. Respondents were therefore questioned about their familiarity with various hydrogen technologies. Due to its relevance to people's everyday lives, hydrogen end-use applications are more well-known as compared to hydrogen production and hydrogen storage, as shown in Figure 17. Since they are more frequently mentioned in the media for the production of renewable hydrogen and refueling stations, water electrolysis and liquid hydrogen are more recognized.

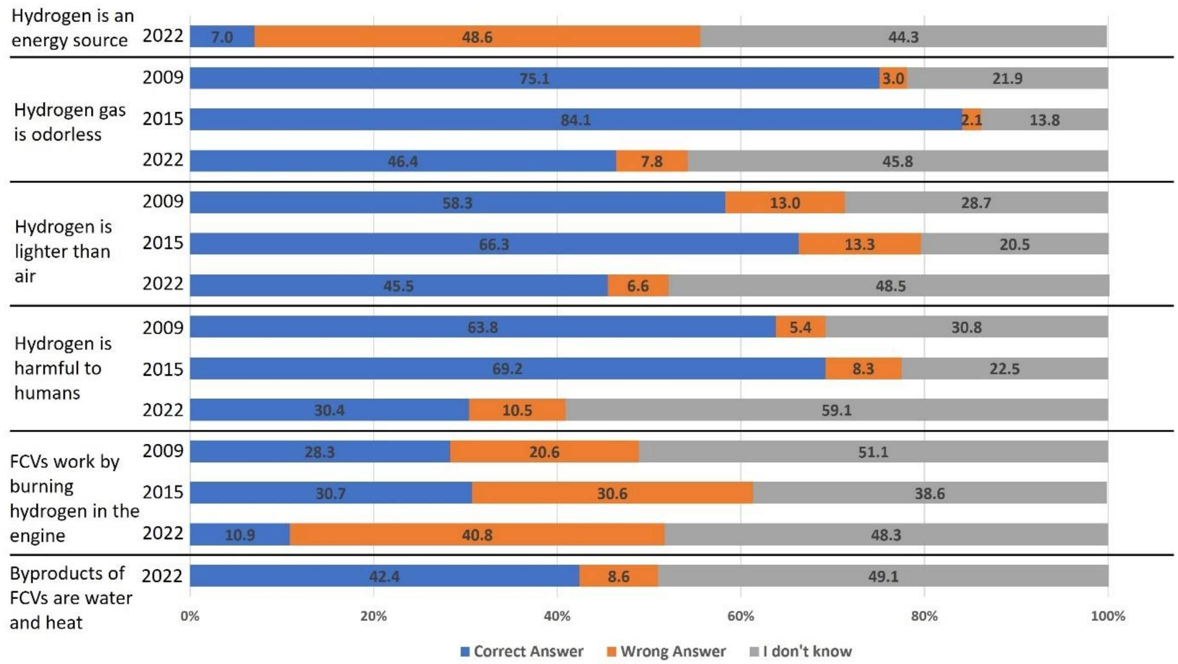

Figure 18: Objective knowledge on the properties of hydrogen and fuel cell vehicles

Six questions about the properties of hydrogen and fuel cell vehicles were specifically developed to gauge public knowledge on hydrogen, as shown in Figure 18. Apart from the question of whether 'hydrogen is an energy source', around 30% of the respondents correctly answered all the properties of hydrogen. Compared to the 2009 and 2015 surveys, fewer people in the 2022 survey answered each question correctly. The question with the lowest percentage of correct responses (7%) asked whether hydrogen is an energy source (as opposed to an energy carrier). The majority of the respondents are aware of hydrogen's use as a fuel for vehicles, with 42.4% indicating that the byproducts of fuel cell vehicles are water and heat. In contrast, only 10.9% of respondents are knowledgeable about how fuel cell technology works, especially how it's used together with electric motors. Compared to previous surveys, wherein approximately 30% of respondents answered the question correctly, the percentage of knowledgeable respondents in the current study was notably lower, at 10.9%. However, a significant proportion of respondents opted for the "I don't know" option (48.3%), which was a prevalent response across all questions in the survey. For comparison, removing those who did not give a correct or incorrect answer, the ratio of correct to incorrect answers was still higher across all categories in previous studies. For FCV operation, the ratio was approximately 1.4 in 2009, 1 in 2015, but only 0.27 in 2022, meaning that while in the 2009 study more respondents selected the correct answer than the incorrect one, in 2022 only one in five respondents was correct. It is difficult to argue for any clear reason that this would occur outside of sample variability.

The measure of objective knowledge, as opposed to self-reported knowledge, reveals gaps in public understanding towards hydrogen. Despite objective knowledge being lower in the 2022 survey than in prior years, self-reported hydrogen knowledge was greater in 2022. This discrepancy between objective and self-reported knowledge could be due to a variety of reasons. While the respondents may be aware of hydrogen and its potential applications, their understanding may be limited to a surface level due to a lack of exposure or educational opportunities. For instance, respondents may overestimate their understanding of hydrogen and its technologies, and there are limited opportunities for individuals to truly interact with hydrogen technologies, leading to a lack of familiarity and understanding. Moreover, the public's limited knowledge could potentially be attributed to a perceived lack of relevance rather than a lack of understanding of energy supply chains, which are often integrated into daily life and operate in the background, making them largely unnoticed by the average user, except during energy crises.

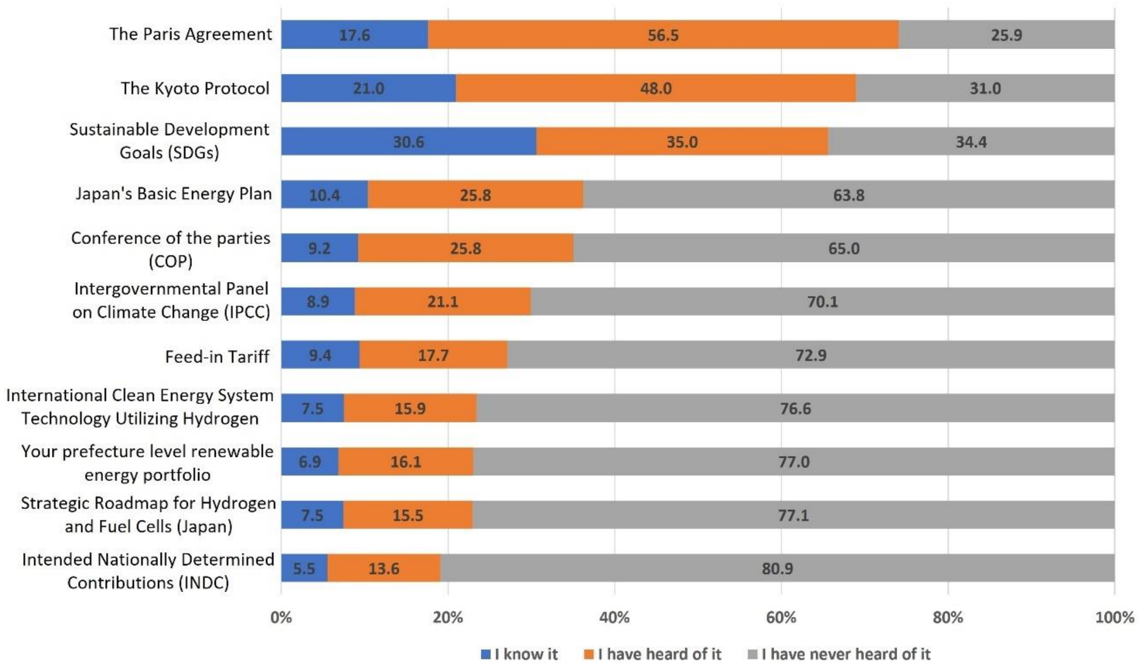

Figure 19: Self-reported knowledge of various energy-related policy

Figure 19 presents the self-reported knowledge of respondents towards various environmental or energy policies. The three policies that people are most aware of by considerable margins are "The Paris Agreement (74.1%)," "The Kyoto Protocol (69%)," and "The Sustainable Development Goals (65.6%)" which we can expect to be a result of continuous media coverage. Despite the Japanese government's promotion of a society based on hydrogen since the 1970s and its regular support for demonstration projects across the nation [12], policies pertaining to hydrogen are relatively unknown in the Japanese society.

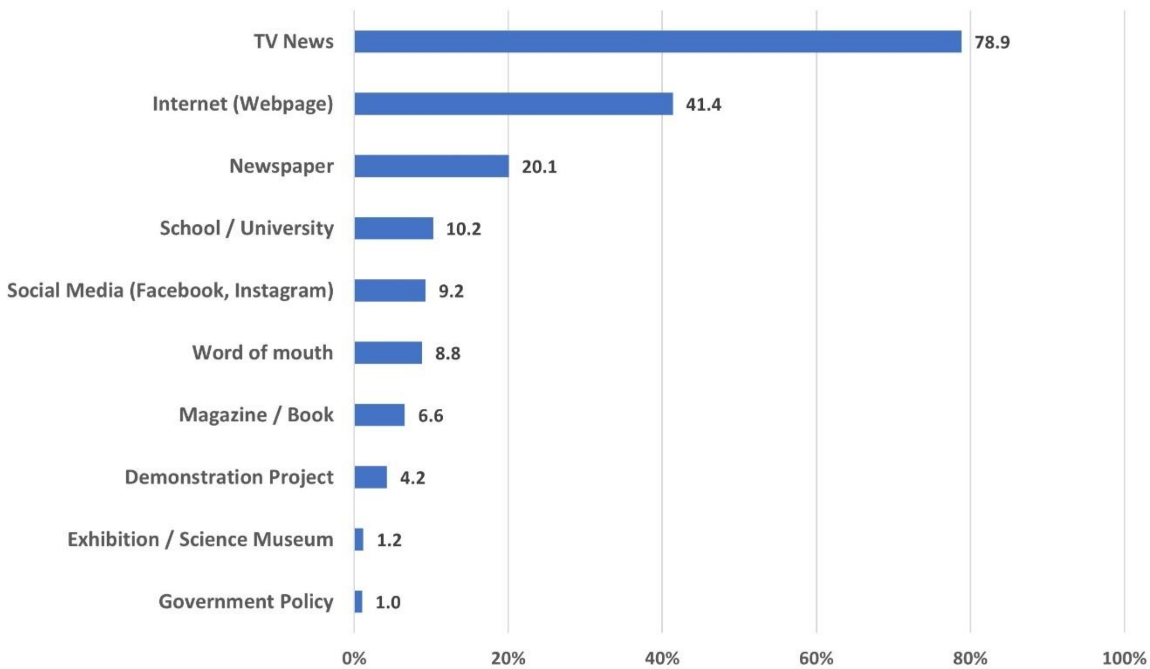

Figure 20: Sources of energy-related information for the respondents

In a follow-up question, respondents were then asked to rank the top three media sources they utilized to keep up with news relating to energy. As shown in Figure 20, the most common sources of information include TV news (78.9%), internet (41.4%), and newspapers (20.1%). It is important to determine the source of a person's information since it is likely to influence their perspective. By emphasizing certain parts of a topic and ignoring others, which is called specific framing [191], the media can influence public perception of hydrogen in a non-neutral way, as well as how these perceptions are evaluated [69], [192]. For example, the majority of media reports positively on the environmental benefits of hydrogen, often ignoring the actual situation surrounding hydrogen production [48]. This may result in people having a perception that differs from the actual situation (see Figure 24). Therefore, fundamental and accurate framing of hydrogen in media coverage is crucial to the communication process.

The public's knowledge and understanding of hydrogen and hydrogen-related technologies appears to be quite limited, which is consistent with the findings of previous survey studies [86], [96]. The rare exceptions are located in a few specific locations where the demonstration project or campaigns increased knowledge and generated public interest [83]. With the exception of a few niche products that are currently available on the market, hydrogen technologies are still in the laboratory or prototype stage, thus there are few opportunities for individuals to really interact with them [83]. When they do, it is most commonly in the form of demonstration projects, which may or may not eventually develop into full-scale, commercial technologies. Furthermore, the potential transition to a hydrogen economy is predominantly discussed among the scientific community, while the coverage of hydrogen in the mainstream media, such as television and news articles, has tended to be sporadic. In addition, the data suggested a general lack of understanding concerning hydrogen properties and related technologies, since very few people were able to answer the questions correctly.

Low levels of public knowledge might reflect a lack of relative importance rather than a lack of understanding of energy technology [93]. Energy is frequently unseen to the average user, especially those who reside in developed countries, apart from during times of energy crises. These crises can be sudden and impact whole populations, as was the case with the energy crisis in the 1970s, or affect the most vulnerable groups, such as people living in energy poverty [193]. Continuing from the last point, energy production stages are frequently remote and unknown, while routes of transportation are often hidden from the public's view, and consumption is integrated into ordinary everyday activities. In addition, energy cost has historically been reasonable for the average user under normal circumstances, and there are rarely any immediate or apparent environmental repercussions [93], [194]. In summary, energy consumption is a common yet mostly unnoticed event for the average user, with the exception of supply disruptions or price increases.

4.3.2 Value

Values and identities at the personal level are critical determinants that drive individuals' actions on environmentally or socially relevant issues such as climate change [188]. Understanding the connection between personal values, identities, and environmental action is important in designing effective communication and engagement strategies that can effectively motivate individuals to take meaningful and sustained action.

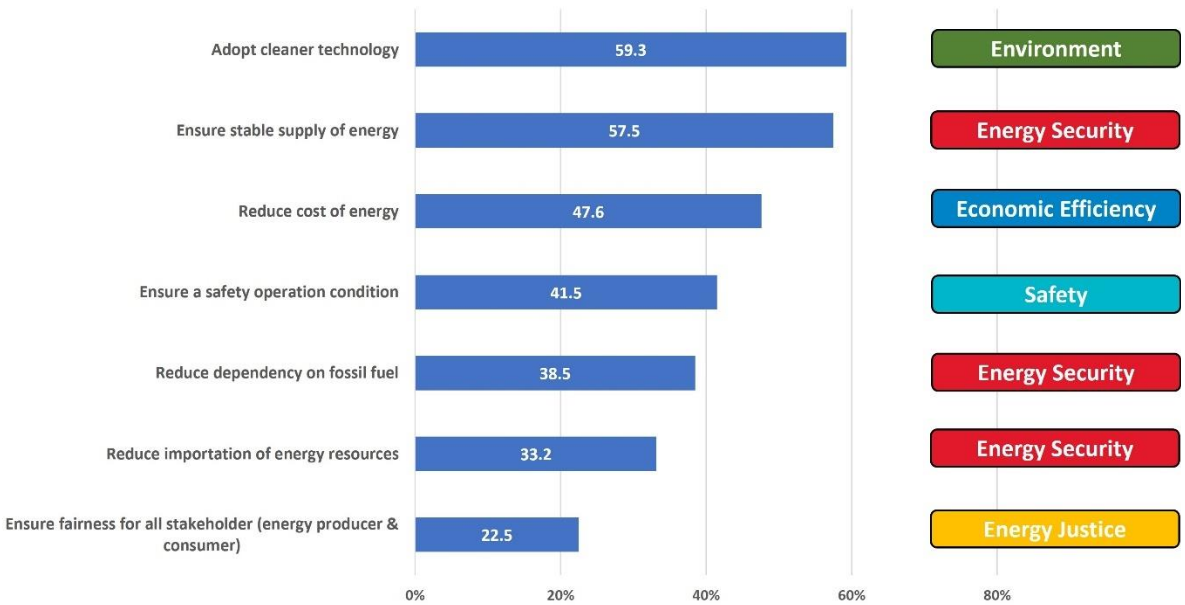

Figure 21: Personal priority in solving energy concerns

Figure 21 presents the results of a survey question where respondents were asked to rank their top three energy concerns that the government should prioritize. This question was designed to align with Japan's "3E+S" energy policy objectives, which aim to balance energy security, economic efficiency, environmental protection and safety in the country's energy mix. An additional statement was included in the survey to assess the respondents' opinions on achieving equity in both social and economic participation within the energy system. The results indicate that adopting cleaner technology to protect the environment is the primary concern among the Japanese community, with 59.3% of respondents prioritizing it as their number one concern. Maintaining energy security, or a stable supply of energy, is a close second, with 57.5% of respondents, while reducing the cost of energy through increased economic efficiency ranks third with 47.6%.

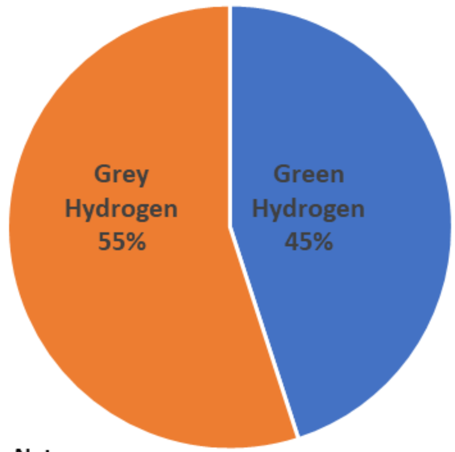

Figure 22: Preference of hydrogen production

In a follow-up question, respondents were asked to select their preferred method of hydrogen production: green hydrogen (described as higher cost but lower emissions) or grey hydrogen (described as lower cost but higher emissions). Green hydrogen is often considered more environmentally friendly than grey hydrogen due to its clean production method, which is produced by electrolysis of water molecules using renewable sources such as wind, solar, and hydropower [1]. This results in significantly lower carbon emissions and a smaller overall environmental impact. However, the production costs of green hydrogen are higher due to the more energy-intensive process and the need for specialized equipment and infrastructure. On the other hand, grey hydrogen, while less environmentally friendly, is currently the most cost-effective method for producing hydrogen [1]. Grey hydrogen is produced using non-renewable sources such as natural gas or coal, resulting in a higher carbon footprint. However, due to the low cost of these resources and the well-established infrastructure for grey hydrogen production, it remains the most widely used method for producing hydrogen on a large scale. Both methods have distinct costs and benefits that will likely impact their acceptance.

It is worth noting that there are also other methods for hydrogen production that seek to balance cost-effectiveness and environmental impact, such as blue hydrogen. This method uses fossil fuels but incorporates carbon capture and storage technology to reduce carbon emissions [1]. As the demand for hydrogen grows, blue hydrogen may become an increasingly viable option as an intermediate phase before transitioning to green hydrogen. However, the option of blue hydrogen was omitted from this question as the objective was to examine the factors of cost and environmental impact of producing hydrogen. The option of blue hydrogen will be included in a future survey to allow for a comparison of different hydrogen production methods.

The results showed a division among the respondents, with 55% opting for grey hydrogen production, and 45% choosing green hydrogen production, as shown in Figure 22. An interesting observation is that among those who prioritized 'adopting cleaner technology' as a government energy concern (n=1401) (see Figure 21), 55.5% favored grey hydrogen production, while 44.5% selected green hydrogen production. This suggests that the consideration of environmental impact alone does not guarantee that individuals will choose the more environmentally friendly method of producing hydrogen, as cost considerations also play an important role.

Although most individuals are aware of the reality of climate change and the importance of environmental conservation, a lack of conversion of this into awareness into action is hindering progress in addressing these pressing issues. In the context of a future hydrogen-based economy, the Japanese community remains divided on the best method of hydrogen production. The findings indicate that both cost considerations and environmental values are of importance in determining the most sustainable method to hydrogen production. To drive more action on climate change mitigation, raising knowledge of the strong environmental values held by others can be an important tactic, especially for those who are not personally highly motivated to take action [188]. This recognition of shared values can be a powerful motivator for individuals to act on the pressing issue of climate change. Furthermore, government and industry must collaborate to lower the cost of green hydrogen production. Governments can establish policies and incentives to promote environmentally friendly, cost-effective methods, while industries can invest in R&D to improve production processes and minimize costs.

4.3.3 Perception

The perception of a hydrogen economy refers to the widespread understanding and outlook on the role and potential of hydrogen as an energy carrier in meeting energy demands and reducing reliance on fossil fuels. It includes beliefs, attitudes, and opinions of individuals towards the viability, feasibility, and sustainability of using hydrogen as an energy carrier. The perception of a hydrogen economy is shaped by various factors, including technical advancements, economic viability, environmental impact, and media influence.

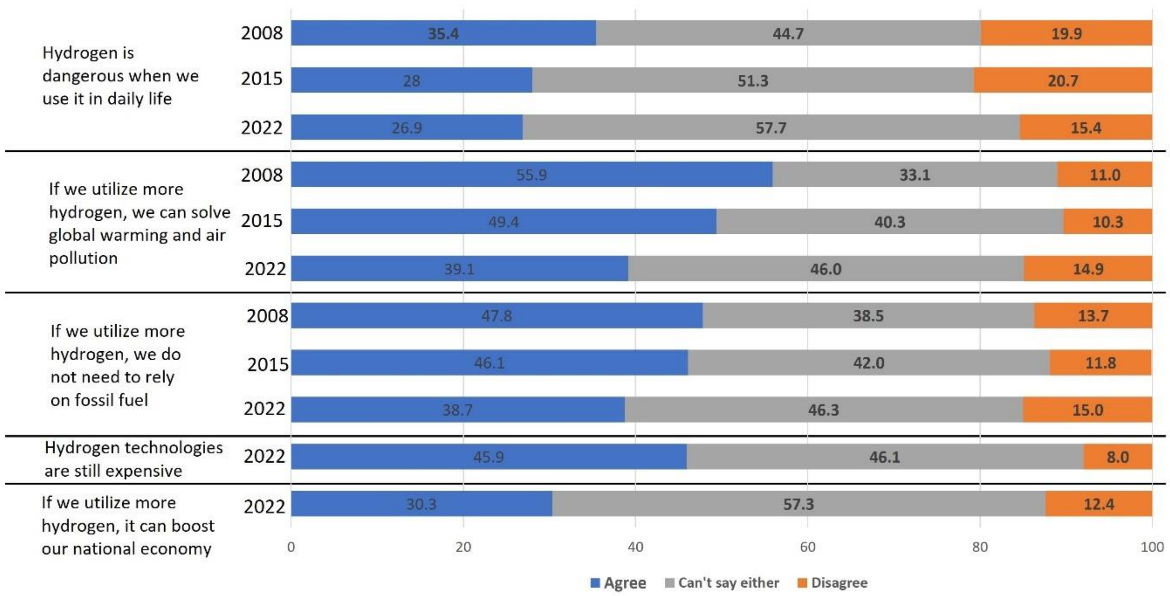

Figure 23: Public perception towards future hydrogen-based economy

In Figure 23, respondents were asked their opinions on five future hydrogen-based economy statements. Three statements were adapted from a previous study by Itaoka et al. [86], while two statements were created specifically for this study. Through all the questions, the public's perception of a future hydrogen-based civilization was predominantly neutral compared to previous years (ranging up to 50% in some cases). The perception of respondents that hydrogen is dangerous when used in daily life had declined marginally (26.9%), however more people responded neutrally (57.7%) than disagreed (15.4%). At the same time, a decline in optimism can be observed over the potential reduction of reliance on fossil fuels (38.7%) and the use of more hydrogen energy to combat global warming (39.1%). As for economic factors, almost half of the respondents (45.9%) believe hydrogen technologies are still too costly, making it difficult for consumer adoption. On the other hand, hydrogen is often touted by governments as a catalyst for job creation and economic growth in sectors like energy, transportation, and manufacturing [178]. Despite its potential benefits, the responses to the idea of a hydrogen-based economy are mixed. People are cautious about the high costs involved in the transition, with 57.3% having a neutral stance, 30.3% agreeing, and 12.4% disagreeing. In short, the perception of hydrogen economy varies, with some people viewing it as a promising solution to reducing greenhouse gas emissions and dependence on fossil fuels, while others view it as having significant technological and economic challenges that need to be addressed.

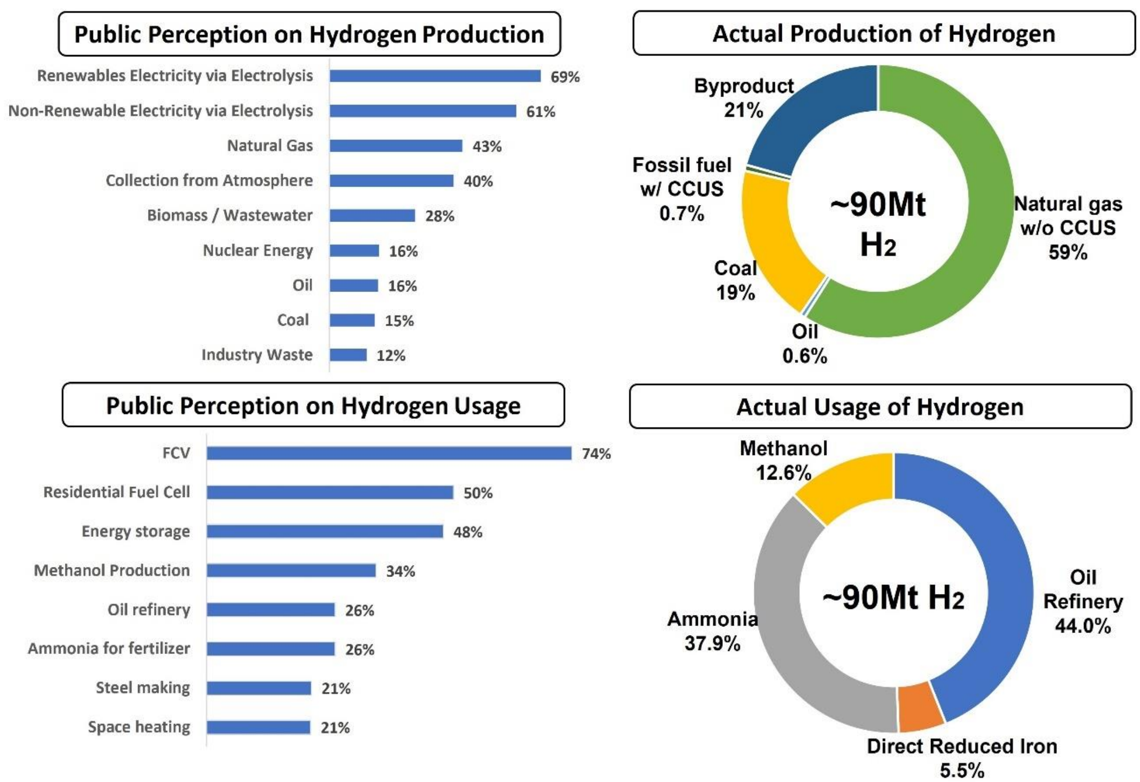

Figure 24: Comparison of public perceptions and reality of hydrogen production and usage

How the general public perceives the technology can be determined by what they associate with hydrogen. In a recent survey conducted in 2019, New Energy and Industrial Technology Development Organization (NEDO) examined Japanese citizen's about their first image associated with the term "hydrogen" [195]. The survey reveals that they were mostly neutral and centered on topics such as "hydrogen water [196]", water (H_2O) and the chemical element "H". People's perception of hydrogen's environmental friendliness is mostly because its byproduct is water, which they believe is not harmful [195].

In Figure 24, respondents were asked to rank the top three production and usage methods of hydrogen from a list of answers. A report published by the IEA in 2021 details the actual production and utilization of hydrogen [13]. Many individuals believe that, in addition to natural gas (43%), electrolysis using either renewable (69%) or non-renewable electricity (61%) is currently used as a major production method for hydrogen. The results are not aligned with the actual production of hydrogen, which consists primarily of natural gas (59%), industrial byproducts (oil / petroleum coke) (21%), and coal (19%). An interesting finding is that 40% of respondents believe that the supply of hydrogen is derived by capture from the atmosphere. Similarly, many individuals believe that hydrogen is primarily employed in clean technologies such as fuel cell vehicles (74%), residential fuel cells (50%), and energy storage (48%). In actuality, hydrogen is utilized in oil refineries (44%) and in the manufacture of ammonia (37.9%) and methanol (12.6%). Although people generally have a neutral perception of hydrogen, with a positive inclination reflected in the higher number of positive responses compared to negative ones, their perceptions of its production and application diverges from the actual reality. This discrepancy further reinforces the knowledge gap in public understanding of hydrogen, as demonstrated by the comparison between self-reported knowledge and objective knowledge of the respondents. It can stem from a lack of accurate information or an incomplete understanding of the hydrogen economy, which leads to a skewed view of hydrogen that does not accurately reflect the reality.

According to this survey, most people's perceptions toward hydrogen as a part of the energy system were neutral, with the majority of remaining respondents leaning towards a positive perception, indicating acceptance. However, these favorable responses were accompanied by a lack of experience, familiarity, or knowledge as indicated in the previous section. This finding contradicts the assumption that the public holds mainly negative opinions about hydrogen [83]. A common dynamic seen in emerging technologies is the initial positive perceptions combined with a low level of knowledge, such as in the case of renewable or hydrogen-based technologies [197].

Public perceptions are formed by the combination of individual experiences, internal values, and external viewpoints [69]. Modern society enables individuals to choose which media outlets to follow and how to acquire information. However, the accuracy and reliability of mass media are a matter of global concern, given that most mass media may emphasize deliberated and hype reporting to attract people's interest [70], [126]. As a result, the viewpoints shaped by mass media may contribute to forming public perceptions in a biased, non-neutral way [198]. This raises fundamental questions regarding how to engage the public in meaningful communication about the complexities surrounding hydrogen, such as the various methods of production. It is essential for stakeholders in the energy sector to engage with the public and provide clear and accurate information about hydrogen to bridge the knowledge gap and build trust and support for its wider adoption and integration into the energy mix.

The studies of public perceptions are to comprehend, characterize, and explain what the public understands and believes about emerging technologies, as well as how they have responded or may respond to their implementation. This will facilitate communication between governments, industry, academics, and the public in providing accurate and reliable information about the current state of the technology. Although understanding public perceptions is not a guarantee of acceptance, the absence of such information will likely result in failure [93].

4.3.4 Acceptance

Public acceptance of the hydrogen economy refers to the level of support and willingness of the general public to adopt hydrogen as an energy carrier [70]. The level of public acceptance may be influenced by various factors such the availability and accessibility of hydrogen infrastructure, the utilization of hydrogen-based technologies and the perception of its safety.

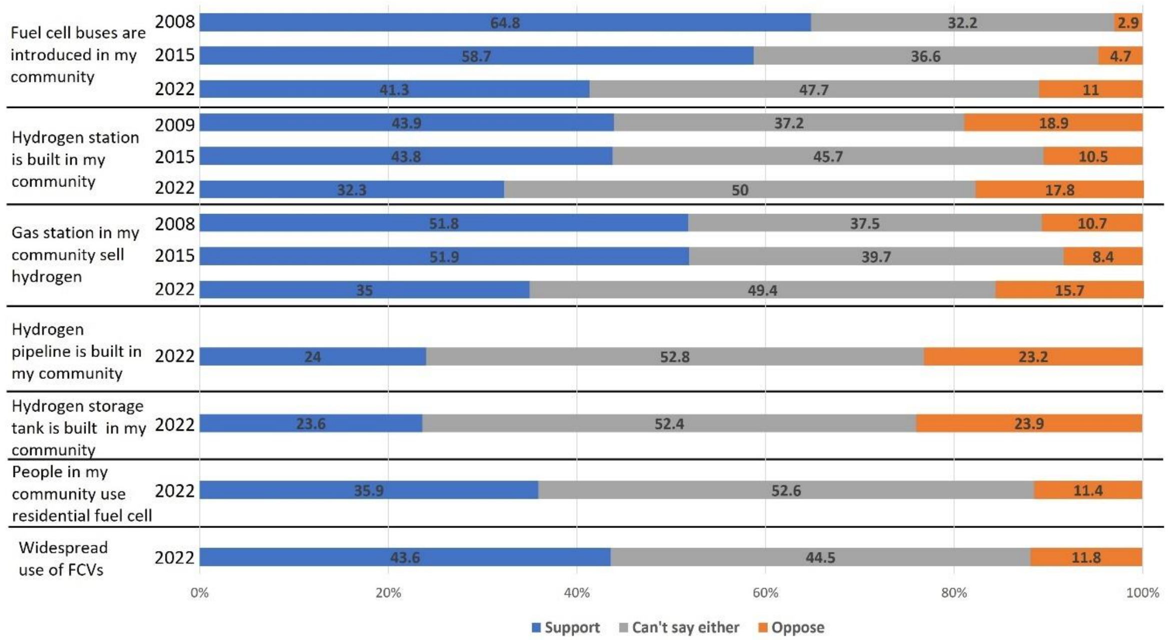

Figure 25: Public acceptance towards hydrogen-based economy

The acceptability of a future hydrogen-based economy was assessed by surveying respondents on their perspectives regarding hypothetical scenarios, as depicted in Figure 25. To comprehend historical acceptance of hydrogen, the results were compared with previous surveys using the response options "Support," "Oppose," or " Can't say either." Compared to previous years, the current survey shows a shift towards a more neutral stance on public acceptance of hydrogen economy, mirroring a shift in public perception (see Figure 23). This change may be due to a growing understanding of the hydrogen economy's potential benefits, as well as increased knowledge of its limitations and challenges. The level of acceptance for various hydrogen-based applications showed variability. The most positive response was observed for fuel cell buses and fuel cell vehicles, with 41.3% and 43.6% of respondents showing support, respectively. This is likely due to the perceived benefits of hydrogen vehicles (fuel cell vehicles & fuel cell buses), such as being environmentally friendly, quiet, and clean. On the other hand, the implementation of hydrogen stations and the conversion of existing gas stations to sell hydrogen received a generally acceptable response with 32.3% and 35% support respectively. However, the proposal to install hydrogen pipelines and storage tanks in communities faced more resistance compared to other hydrogen-based technologies, with roughly equal levels of support and opposition among respondents.

The level of acceptance for hydrogen vehicles is notably higher than the acceptance for the installation of hydrogen stations and gas stations that sell hydrogen. The deployment of hydrogen stations and gas stations that sell hydrogen is critical for facilitating the widespread adoption of hydrogen vehicles, given that these vehicles require a source of hydrogen to power their fuel cells. Nonetheless, some respondents have shown resistance to the installation of such infrastructure due to safety concerns, as highlighted in Figure 26. These concerns often arise from the perceived risks of hydrogen leakage, explosions, or fires, leading some individuals to be hesitant in supporting the installation of hydrogen stations and gas stations that sell hydrogen in their communities.

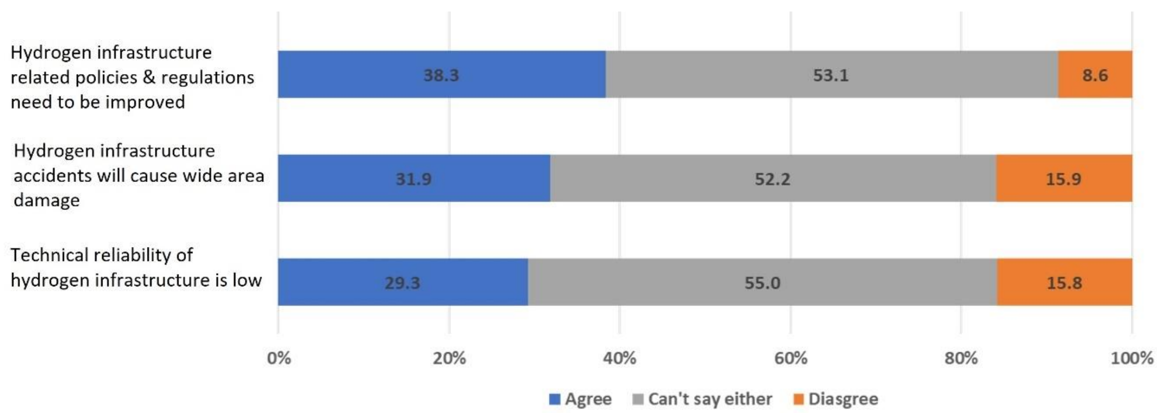

Figure 26: Risk perception of hydrogen infrastructure

Figure 26 shows that approximately half of the respondents had a neutral stance (were unable to say that they agreed or disagreed), while twice as many of the remaining respondents considered that there were safety risks associated with hydrogen infrastructure (hydrogen stations, hydrogen pipelines, hydrogen storage tanks). These respondents believed that hydrogen infrastructure is not considered to be reliable (29.3%) and may cause widespread damage in the event of an accident or malfunction (31.9%). This highlights the need for improvements in related policies and regulations to address public concerns and ensure the safety and reliability of hydrogen infrastructure, an issue that 38% of respondents agree on.

Risk perception is an important topic when considering large scale technology change. However, from a risk perspective, there is the perceived risk, as well as the actual risk. Perceived risk of hydrogen refers to the general public's perception of the safety of hydrogen and its use, which is often influenced by media coverage and past incidents. The public is likely to overestimate the risk of hydrogen due to unfamiliarity with the technology, resulting in a perception that is higher than the actual risk due to the reputation of hydrogen being highly flammable and explosive, leading to fear of its use [199]. Actual risk of hydrogen, on the other hand, refers to the real and quantifiable risks associated with hydrogen and its use. Hydrogen can be a safe fuel when properly handled and used with appropriate safety measures and guidelines in place [200]. In comparison to traditional fossil fuels, hydrogen has the potential to be much safer, as it is non-toxic and disperses quickly in the atmosphere in the event of a leak [201]. It's important to note that the actual risk of hydrogen can be further reduced through proper handling, storage, and transportation, making it a safe option for various applications, including transportation, energy storage, and industrial processes [202]. Furthermore, improving public understanding of the safety of hydrogen and addressing these concerns through education and communication efforts can help to improve the risk perception of the hydrogen economy and increase its public acceptance.

Public acceptance of the hydrogen economy varies across different technologies but tends to be positive, except for cases of neutral stance. The transportation sector has shown particular interest in using hydrogen to reduce greenhouse gas emissions, reflecting a growing recognition of the need for clean energy solutions. In addition, support for the hydrogen economy is also being driven by government policies and investments in research and development, as well as private sector investments in fuel cell technology and infrastructure.

One of the most critical aspects to note is hydrogen-based technologies distinguish themselves from other energy technologies by their multi-stage acceptance criteria, as the concept of a hydrogen economy encompasses the entire energy supply chain [1]. To explain this further, renewable energy and end-use technologies such as photovoltaic panels and electric vehicles only require public acceptance at their respective stages of production or usage. Furthermore, both energy technologies utilize the familiar energy carrier, electricity. As a result, creating a successful hydrogen economy presents a unique challenge, where any shortfall in public acceptance at any stage can affect the entire supply chain. A lack of support for a particular method of hydrogen production can lead to negative consequences for the acceptance of hydrogen storage, transport infrastructure, and hydrogen-based applications, and the reverse is also true. High levels of public acceptance can lead to increased investment and development in the hydrogen economy, while low levels of acceptance can hinder its growth and adoption. In order to further advance public acceptance of the hydrogen economy, it will be important to continue to educate the public and address any concerns they may have, while also advancing the technology to make the hydrogen economy a more viable and attractive option.

4.4 Conclusion

This study assesses public knowledge, perception, and acceptance of hydrogen technologies by comparing the results of a community survey conducted in March 2022 to previous surveys. It provides a different perspective by examining the hydrogen technologies from a system perspective, an aspect that is often overlooked in other studies. Additionally, surveys only capture public attitudes at a single point in time [93], so comparing surveys addresses the limitations of survey-based methodology in providing a comprehensive understanding of changing attitudes over time. The results indicate some variations resulting from the survey sample and reference year, and can be summarized as:

- The objective knowledge of hydrogen is lower than self-reported knowledge, indicating a gap in public understanding. The objective knowledge of hydrogen has decreased in the 2022 survey compared to previous years, but self-reported knowledge has increased.
- The public's limited knowledge might be attributed to a lack of perceived relevance instead of a lack of understanding. Energy supply chains are often integrated into daily life and operate in the background, making them largely unnoticed by the average user, except during energy crises.
- The surveyed Japanese respondents were split on the choice between green hydrogen and grey hydrogen production. Cost and environmental factors both play a crucial role in determining the most suitable method for hydrogen production.
- In the short term, blue hydrogen may be a viable option to balance cost-effectiveness and environmental impact as an intermediate phase before transitioning to green hydrogen.
- Public perception of hydrogen is neutral, with a positive inclination, but their understanding of its production and utilization diverges from the

actual reality, which leads to a skewed view of hydrogen that does not accurately reflect the reality.

- The level of acceptance for different hydrogen-based applications varied. Among end-use applications, transportation received the most support, followed by refueling infrastructure and storage infrastructure.
- The results of the current survey showed a predominantly neutral response compared to previous years, which leads us to consider the necessary strategy to educate the public and provide reliable information on the status of the technology.

The results of the survey, which was a representative sample of the Japanese population, indicate that respondents are generally more accepting of the use of hydrogen in the transportation sector. This aligns with the Japanese government's plans to expand the use of fuel cell vehicles in the near future [38]. However, fuel cell vehicles face stiff competition from battery electric vehicles in the passenger sector due to the rapidly declining cost of batteries [203]. Opportunities may exist in the long-haul trucking sector, which faces significant challenges in decarbonization due to factors such as long distances, unpredictable routes, and strict regulations. Battery electric trucks are not yet a practical option for this sector due to the heavy weight of batteries, slow charging speeds, and lack of infrastructure for electrification on remote routes [204]. Fuel cell trucks present an opportunity to decarbonize the long-haul trucking sector due to faster refueling speeds and lower weight compared to batteries, which can increase payload capacity. Furthermore, the establishment of refueling infrastructures along long-distance routes in addition to urban areas is expected to have a positive impact on the adoption of fuel cell vehicles in the passenger sector [203].

Another important point concerns the production of hydrogen. Currently, hydrogen is predominately produced by non-renewable sources with high carbon emissions [13]. Green hydrogen has not yet reached a stage where it can compete with grey hydrogen on a cost basis, and only represents a small proportion of the market [13]. If there is an increase in demand for hydrogen, this will result in the challenge of sustainably producing cost-efficient and environmentally friendly hydrogen. Therefore, investment policies can be focused on blue hydrogen in the short term to balance between cost-effectiveness and environmental impact, which are significant considerations in the Japanese community (according to the survey). This could serve as an intermediate stage before making the transition to green hydrogen. However, it is important to set a timeline to phase out blue hydrogen to transition to green hydrogen and avoid the technology lock-in of blue hydrogen production infrastructure. After all, the ultimate objective of a hydrogen economy as it was originally conceived by John Bockris, is to generate hydrogen from renewable energy sources [205].

In recent years, there have been increasing investments and research into the development of hydrogen technologies globally and in Japan, and there are signs that the hydrogen economy is starting to take shape. However, there is also recognition that it will take time and significant effort to fully realize the potential of hydrogen. The current status of the hydrogen economy is optimistic but cautious. There is growing recognition of the potential for hydrogen to play a significant role in the transition to a more sustainable energy future. However, a significant portion of respondents remain neutral or undecided (ranging up to 50% in some cases), reflecting a general unfamiliarity with hydrogen and its potential applications. The question arises, what information the public needs and who they trust as a credible source. The survey reveals the preferred media sources used by the Japanese community to understand energy related news, which can differ from those used in other countries. To effectively disseminate information, the Japanese government should focus on utilizing these preferred media sources and address two key issues. Firstly, addressing the knowledge gap that is prolonging the lack of understanding surrounding hydrogen's actual situation. Secondly, addressing public concerns about the safety of hydrogen to differentiate between perceived and actual risks associated with hydrogen. Addressing these issues will enable consumers to make informed decisions regarding hydrogen technologies, which is crucial in promoting wider acceptance and understanding of hydrogen as a future energy carrier.

In conclusion, understanding public acceptance of hydrogen, therefore, allows for potential objections to be identified early on and to influence the development and diffusion of the technology. The acceptance of the hydrogen economy is a multi-faceted and multi-stage challenge, encompassing a range of actors including community, market, and government acceptance. The success of the hydrogen economy will require addressing and overcoming these challenges at each stage of the hydrogen value chain, including production, storage, transportation, and application. The results of this study are expected to improve the current state of knowledge and serve as basic information in establishing a strategy for a future hydrogen economy transition. The goal is to establish an operational, equitable and inclusive hydrogen economy that aligns with the collective desires and needs of all stakeholders.

4.4.1 Limitations & Future Work

This study is one of the first to analyse and describe, using a qualitative approach, the evolving attitudes of the Japanese community towards the hydrogen economy. However, the current study has limitations in exploring complex and unfamiliar topics within the community in depth. Surveys typically rely on closed-ended questions and multiple-choice answers, which can result in limited information and a lack of nuance in the responses. To address the limitations, two approaches can be taken. Firstly, by expanding the scope of the study by incorporating methods such as interviews or focus group discussion to gain a deeper and more detailed understanding of the subjects being studied. Secondly, by conducting quantitative studies that utilize explanation-focused analyses, such as regression models, to determine the impact of specific factors on acceptance. This approach can provide a more data-driven and systematic evaluation of the topic and provide insights into underlying relationships and patterns. Although explanation-focused analyses have been undertaken to examine the public acceptance of fuel cell vehicles [86] and refueling stations [87] in the Japanese community, the public acceptance of the hydrogen economy from a system perspective requires additional evaluation.

Chapter 5 Exploring Transitions to a Hydrogen Economy: Quantitative Insights from an Expert Survey

5.1 Introduction

As global efforts intensify to limit anthropogenic climate change [206], there has been a worldwide shift towards carbon neutrality [207], [208]. This involves a combination of initiatives such as reducing greenhouse gas emissions [208], transitioning to renewable energy sources [209], implementing carbon capture technologies [210], and promoting sustainable practices among both industries and individuals [211]. The pledge towards carbon neutrality has been gaining significant momentum, with major nations like the United States, China, and the European Union, as well as smaller emerging nations, committing to achieve a net-zero target by 2050 in mitigating global climate change [212]. However, achieving this will require decarbonization across various sectors [213], [214], including power [215], transportation [216], buildings [217], and industry [218].

Given its versatility in various sectors, hydrogen is a potential option for decarbonization. While not new [205], it has garnered significant attention again in recent years [13]. The prospect of a hydrogen economy has been incorporated into national energy policies in numerous countries [2]. Yet, the interpretation and proposed implementation of hydrogen varies significantly from one country to another [25]. For instance, Japan has incorporated the prospect of a hydrogen economy into its national energy policy [26], seeing hydrogen as a means to achieve carbon neutrality by 2050. In contrast, Australia perceives hydrogen differently, viewing it mainly as an export commodity [219], indicating the potential for a growing hydrogen export industry. Despite these differences, the varying interpretations and implementations of hydrogen usage underline its potential to revolutionize the global energy landscape. Some view it as a key component for power generation [220], others see it as a strategic resource to store excess renewable energy [221], and some emphasize its role in transitioning towards a greener transportation sector [222].

The wide array of approaches to hydrogen reflects the unique energy landscapes of each country, but they also hint at the potential for international synergies in forging a hydrogen economy. Recognizing the strengths and limitations of each country in the development of a hydrogen economy could pave the way for global collaboration. Reflecting on the journey of the hydrogen economy thus far [46], [47], it is important to recognize that most previously declared milestones have been missed [114], [223], and the pace of progress has been slower than initially anticipated [224]. To understand the reasons behind these delays, it is important to critically evaluate current progress of the transition to a hydrogen economy, as a record for future reference to help the transition towards a hydrogen-based future remain on track.

5.1.1 Research Objective

The aim of this Chapter is to evaluate multinational perspectives of the transition to a hydrogen economy through an expert survey, categorizing results based on the experts' experience levels, the energy trade status of their respective countries, and by contrasting perspectives from both past and present. The study was structured as an exploratory framework with two key objectives. Firstly, it sought to gather expert opinions on past drivers, and barriers to adopting hydrogen technology, as well as the current state of the industry, in order to determine whether these factors have evolved over time. Secondly, the study sought to clarify the different, yet overlapping interpretations of the hydrogen economy among experts from academia, industry and policy making bodies. This expert survey was undertaken in parallel with the community survey in Japan that was described in Chapter 4 [223]. The combined study aims to understand the varying perspectives on the hydrogen economy among diverse social groups, including academia, industry, government, and the general public. The hydrogen economy was initially envisioned as a universal energy carrier that could efficiently produce and distribute hydrogen from renewable energy sources [205]. Recently, the role of hydrogen has evolved, leading to diverse interpretations of a future hydrogen economy and forging connections with social movements such as the just transition [225], which promotes an equitable transition towards a sustainable energy system, referred to as a just hydrogen economy [226], [227].

5.2 Methodology

The present study employed an online survey platform, SurveyMonkey®, for data collection. It invited independent experts from various backgrounds including academics, industry professionals, and policy makers from different geographic regions. The value of conducting expert surveys lies in the wealth of knowledge and experience these experts possess [228], particularly in the field of energy and the hydrogen economy. Their extensive experience allows us to understand the transition across different time periods, as well as the motivations and challenges associated with the hydrogen economy during those times.

The research is characterized as exploratory since it is one of the first studies to explore the global perspective of the hydrogen economy, aside from the report conducted by IRENA in 2022 [2]. The survey questionnaire was developed by referencing questions from previous studies, as detailed in our literature review, which aligns with the objectives of the current research. In total, 15 closed-ended questions and 2 open-ended questions were formulated, covering three main aspects: (i) respondents' background and experience; (ii) interpretation of a hydrogen economy; and (iii) the evolution of drivers and barriers towards a hydrogen economy. The survey consisted of quantitative and qualitative questions designed to gather data on respondents' perspectives regarding different aspects of the hydrogen economy. Additionally, demographic information was collected, including respondents' expertise, knowledge level, and the country on which they based their knowledge about the hydrogen economy. The quantitative questions utilized various response formats, such as Likert scales, multiple-choice, and checkboxes. Furthermore, open-ended qualitative short answer questions were included in the survey to allow respondents the chance to express their opinions and provide additional information that might have been overlooked in the questionnaire. In order to ensure a standardized understanding between the author and respondents, a description for each answer choice was provided. This was done to address the issue raised in previous studies [83], [96], where it was noted that answer choices were not clearly defined, leading to potential variations in interpretation among different respondents. The survey required approximately 10 minutes to complete, and respondents had the option to indicate whether they were willing to participate in further discussions.
The survey was targeted at experts through purposive sampling, and respondents were given the option to recommend other knowledgeable individuals well-suited to participate (a technique known as snowball sampling) [103]. The initial approach involved a prior systematic literature review conducted by the authors [112], with a focus on authors who had contributed to papers related to the hydrogen economy. The second approach involved the

exploration of energy institutions' websites and participation in hydrogen-related conferences, such as the World Hydrogen Energy Conference, which provided additional prospects for respondent sourcing. Participation in the survey was voluntary and carried out anonymously.

This study is part of a broader research effort that utilizes a two-stage Delphi Method involving a first-round survey questionnaire and a subsequent round of discussions. To summarize and interpret the characteristics of the data obtained from the first-round survey questionnaire, descriptive analysis was conducted. This study presents the findings derived from the first-round survey questionnaire, while the findings from the subsequent round of discussions will be addressed in a separate study as the second part of the research. Our research approach employed mixed methods [229], [230], encompassing both quantitative and qualitative data to obtain a comprehensive understanding of the topic. Given that the research questions did not involve measuring differences between variables, statistical tests such as regression models were not used. It was not mandatory for respondents to answer every question, so the values shown may not represent the total number of responses received. Unless stated otherwise, the percentage values displayed are calculated based on the number of respondents who provided an answer to the specific question.

5.3 Results & Discussion

This research aimed to gain insights into expert opinions regarding the development of the hydrogen economy, as well as their perceptions of the drivers and barriers to its advancement. The subsequent section presents a descriptive analysis of the survey results and discusses their implications. The survey was conducted in June 2023 and received responses from a total of 65 participants, which is considered a sufficient volume of data in comparison to other expert surveys reviewed in our literature review.

A total of five questions were asked to identify the respondents' professional backgrounds, their depth of experience within the energy and hydrogen sectors, and their willingness to engage in a subsequent interview. Rather than focusing on the respondents' places of origin, the survey explicitly inquired about the country that shaped their knowledge or experience within the hydrogen economy.

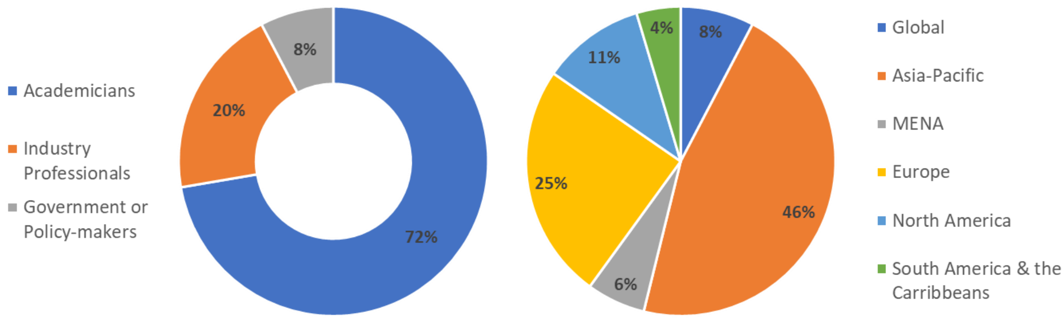

Figure 27: (Left) Expertise Breakdown of Respondents (Right) Regional distribution of knowledge on the Hydrogen Economy (n=65)

As illustrated in Figure 27, the respondents' areas of expertise have been categorized and presented along with a regional distribution that underscores the geographical influence on their understanding of the hydrogen economy. The categories include:

- Academicians, which encompasses professors, researchers, scientists, and educators in academia.
- Industry Professionals comprise engineers, energy consultants, technology developers, financial analysts, manufacturing supervisors, and energy journalists.
- The Government or Policy-Making category includes government officials, regulators, policy makers, and members of international organizations.

The survey primarily targeted authors who have contributed to journal papers and conferences, leading to a respondent composition of 72% Academicians, 20% Industry Professionals, and 8% Government or Policy Makers. This distribution differs from the global survey conducted by IRENA [2], which primarily includes IRENA members and topical experts. A total of 65 experts from 22 countries responded to the survey, with the highest regional distribution observed in the Asia Pacific region (46%), followed by Europe (25%), North America (11%), the Middle East & North Africa (MENA) (6%), and South America & the Caribbean (4%). Interestingly, 8% of respondents focused on the global trend of the hydrogen economy rather than specific countries.

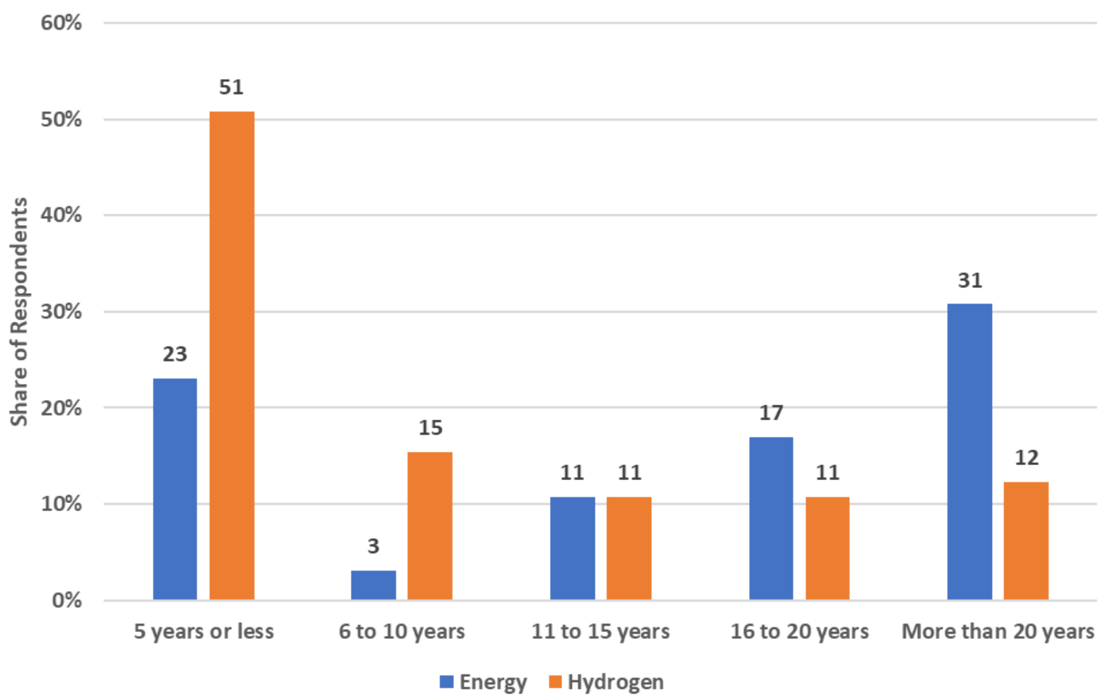

Figure 28: Comparison of experience levels in energy and hydrogen among respondents (n=65)

Figure 28 illustrates the comparison of experience levels among respondents within the energy and hydrogen fields. The findings reveal a diverse range of experience levels among the surveyed experts. In the hydrogen field, a significant number of respondents (51%) have less than five years of experience, indicating the representation of emerging experts. Conversely, the energy field exhibits a higher proportion of seasoned experts, with approximately 31% of respondents reporting 20 or more years of experience, compared to only 12% in the hydrogen field. The inclusion of respondents with varying experience levels contributes to the study's comprehensiveness and relevance, capturing insights from both seasoned experts and individuals new to the field. The mean experience level of the 65 experts who participated in the survey on the energy field was 16.8 years, while in the hydrogen field, it was 9.3 years.

As may be expected, the years of experience in the energy field are distributed across a wider range, with the majority of experts having around 10 years of experience or more. In contrast, the hydrogen field shows a different pattern, with most experts have significantly fewer years of experience, with the highest frequency being around 5 years or less. This likely reflects the recent growth and investment in the hydrogen industry compared to the broader energy sector, despite the long history of the hydrogen economy and various sectors utilizing or producing hydrogen. The length of time in the field is important for understanding the time period which the experts are familiar with and that they would be expected to reflect on in their responses.

5.3.1 Current Progress and Future Projections

The first key question to the experts was to try to understand the extent to which the hydrogen economy has made actual progress to date, and the expectation of its potential in the future.

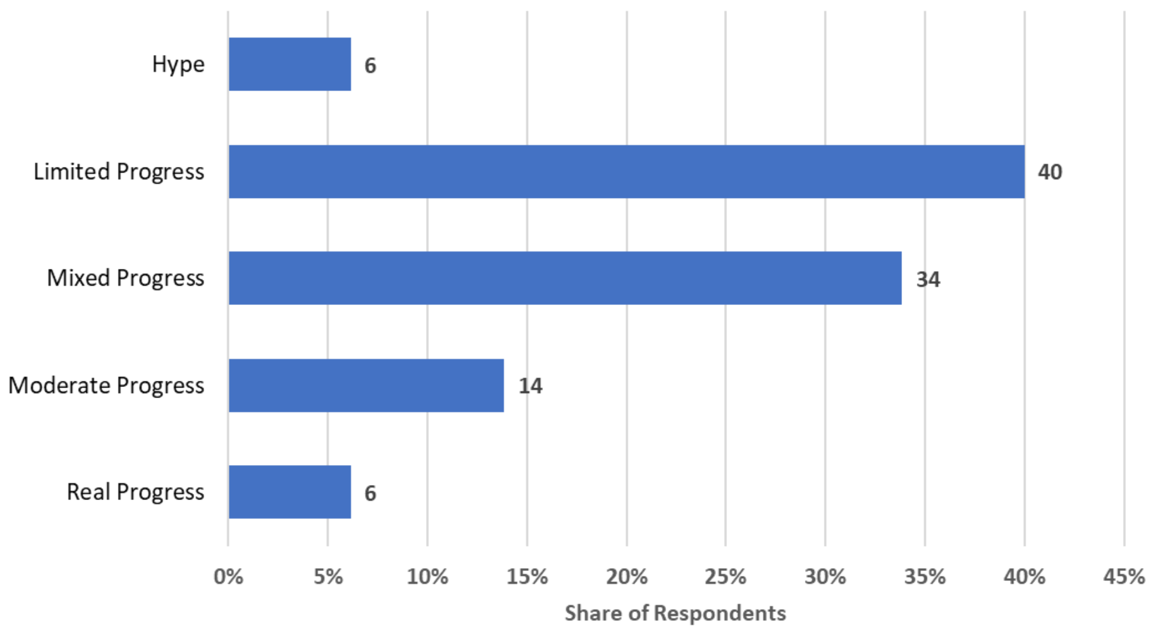

Figure 29: Evaluating progress of the hydrogen economy (n=65)

Figure 29 illustrates the opinions of experts regarding the progress of the hydrogen economy to date. The results are divided into five distinct categories: “Real Progress”, “Moderate Progress”, “Mixed Progress”, “Limited Progress”, and “Hype”. Less than one quarter of the experts held a positive view on the progress of the hydrogen economy. Specifically, 14% see "moderate progress," acknowledging meaningful developments but recognizing the challenges that still need to be addressed. Only a small fraction (6%) believe there has been "real progress," indicating significant advancements that position the hydrogen economy as a rapidly developing and viable alternative to fossil fuels.

On the other hand, an equal number of experts (6%) dismiss the hydrogen economy as being more "hype" than reality. This suggests that the attention it has received has not been matched by substantial development, making it unlikely to become a significant player in the global energy landscape. The majority of experts perceive either "limited progress" (40%) or "mixed progress" (34%) in the development of the hydrogen economy. Those who believe in "limited progress" see the hydrogen economy as largely underdeveloped, with minor improvements in production, storage, distribution, and utilization. Those with the "mixed progress" view acknowledge advancements in certain areas but note stagnation or challenges in others, making it difficult to determine the future implementation of hydrogen as a dominant energy carrier. This suggests that the majority of experts feel that the hydrogen economy has not advanced as much as it could or should have.

Overall, the data implies a degree of skepticism or caution among experts regarding the advancement of the hydrogen economy. This skepticism is perhaps not surprising, considering the observed hype cycles in the hydrogen economy's development over the past decades (see Figure 11). These cycles, marked by surges in academic publications, media coverage, and industrial projects, have often led to inflated expectations without sustainable progress. Each hype cycle tends to be characterized by a degree of "blinded enthusiasm," in which the potential of hydrogen as a solution for climate change is overstated, often ignoring the disappointments of previous cycles. While a small proportion see substantial progress or view current discussions as hype [127], [130], the majority perceive progress as limited or mixed. This view aligns with the cyclical and nonlinear nature of technological transition as evidenced in other fields like renewable energy. Although the hydrogen economy has not yet lived up to its utopian image, there have been real advancements. For example, the efficiency of both fuel cells and electrolyzers has been increasing while their costs have been decreasing [174]. In light of this, it's important to note that roadmap targets for the hydrogen economy are often overly optimistic, much like their renewable energy predecessors. However, as with renewable energy, this does not negate the actual progress that has been made. This suggests that more work needs to be done for the hydrogen economy to fully realize its potential [1]. This may call for focused research, investment, and policy support to overcome the existing challenges and speed up the development and adoption of hydrogen technologies.

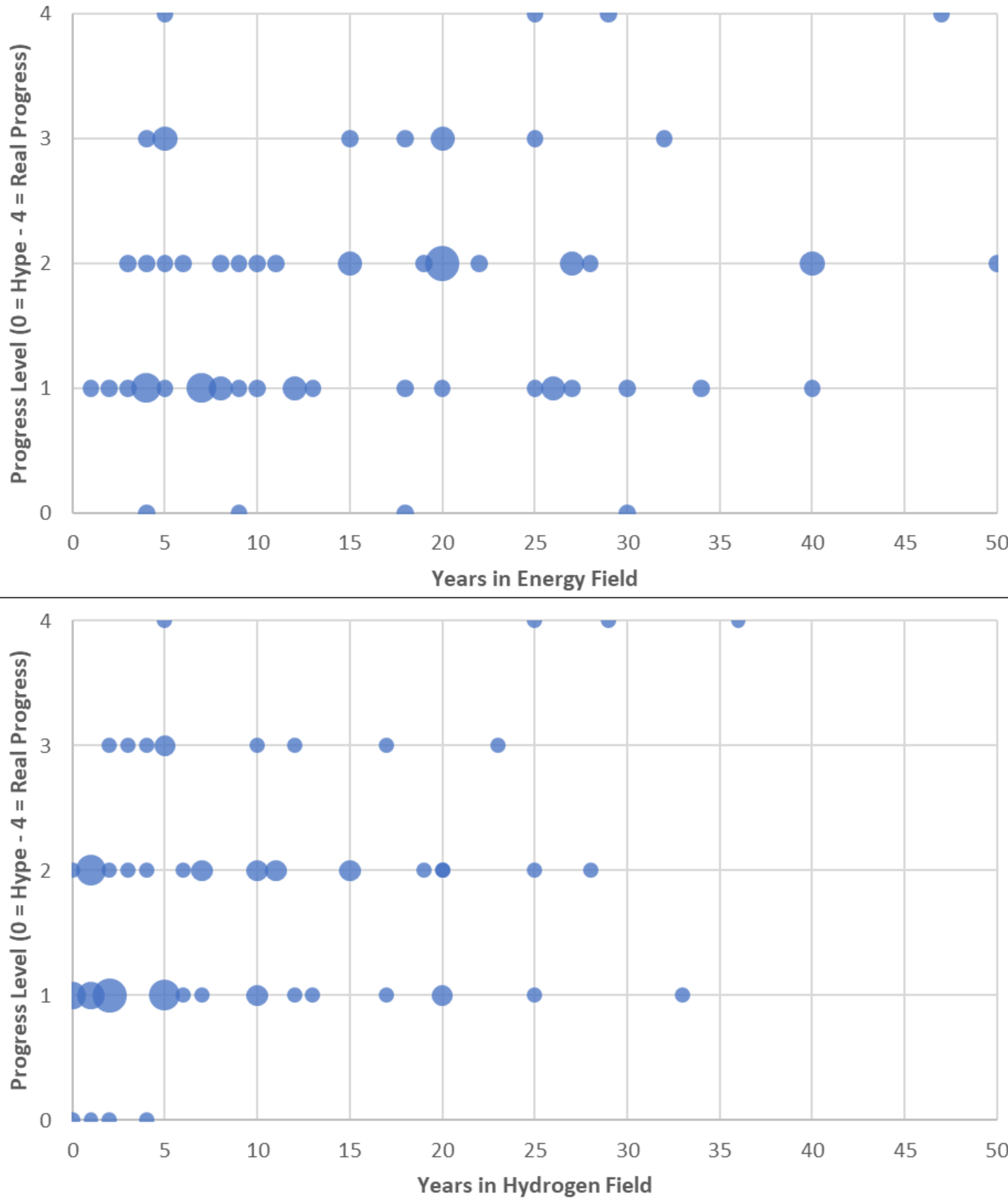

Figure 30: Experts` level of experience (energy (top) & hydrogen (bottom)) and perception of hydrogen economy progress (n=65) (For this plot, the Progress Level was nominally allocated a number from 0 – Hype, 1 – Limited progress, 2 – Mixed progress, 3 – Moderate progress, 4 – Real progress)

In Figure 30, the scatter plots visualize the relationship between years of experience in the energy and hydrogen fields and the perceived progress level of the hydrogen economy among the experts. Observations from both plots show that there is no clear correlation between years of experience in either the energy or hydrogen fields and the perceived progress level. The data points are evenly distributed across the experience ranges, indicating that perception of progress is not significantly dependent on the years of expertise in either field. The majority of experts, regardless of their experience, perceive the progress of the hydrogen economy as "Limited Progress" or "Mixed Progress." Only a few experts perceive it as "Real Progress," and these individuals have diverse years of experience, further suggesting that perception of progress is not strictly tied to experience. Furthermore, some experts with extensive experience (more than 20 years) perceive the progress of the hydrogen economy as "Hype" or "Limited Progress," highlighting that despite the longer timeframe of reference, there was not an overall perception of progress. There may indeed be some difference in the frame of reference over which individuals are considering progress, which could affect the responses, but this survey is not able to explicitly obtain such a relationship.

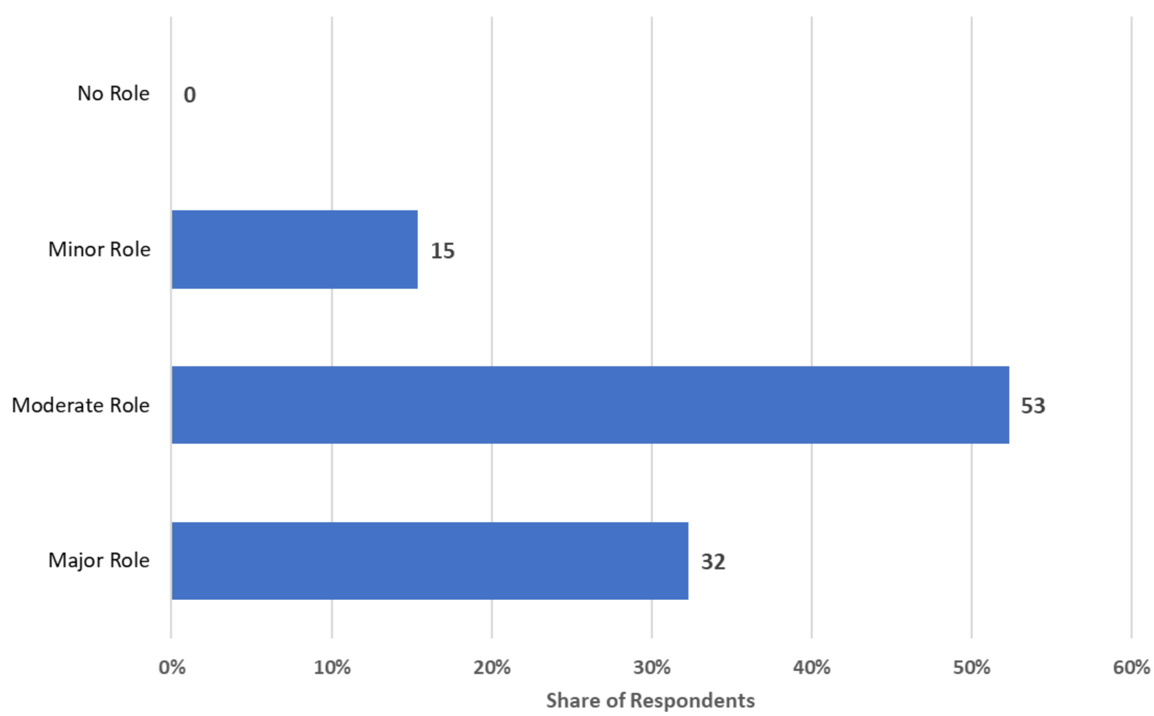

Figure 31: Evaluating the role of hydrogen in future by the year 2050 (n=65)

Figure 31 depicts expert opinions on the projected role of hydrogen in the energy sector by the year 2050. The results are categorized into four distinct groups: “Major Role”, “Moderate Role”, “Minor Role”, and “No Role”. Each category reflects the level of impact the experts anticipate hydrogen will have in the future.

A majority of experts, 52%, predict that hydrogen will play a "moderate role" by 2050, operating as one of several clean energy resources. This suggests a majority consensus that hydrogen will be an important component of the energy sector, but it might not necessarily dominate or replace other energy resources. 32% of experts believe that hydrogen will play a “major role” by 2050. These experts foresee hydrogen as a crucial, potentially dominant, part of the energy mix, possibly indicating a significant shift toward hydrogen-based technologies and applications. A smaller proportion, 15%, of the experts believe that hydrogen will have a "minor role," serving as a niche technology with limited applicability. These experts likely see other clean technologies as more viable, scalable, or cost-effective.

It is evident that experts believe hydrogen will play a role in the future of energy, although the extent of its impact varies. Most experts see it playing a moderate role, contributing to a diversified and multifaceted approach to renewable energy. However, a significant number also believe it has the potential to take a leading role, indicating that the potential of hydrogen should not be underestimated.

Figure 32 illustrates the expert opinions on the above two related aspects of the hydrogen economy: its current progress and its future role by the year 2050. The results have been categorized into two levels of hydrogen experience: those with 5 years or less, and those with 6 years or more, roughly correlating with the recent surge in hydrogen interest and splitting the respondents into 2 almost-equal groups. In addition, Appendix Part B documents the results for those with energy experience, using the same categorization. (See Figure 44 for comparison with Figure 32). Despite the different views about the current state of progress, which is mostly limited or mixed, opinion remains positive of a future where the hydrogen economy plays a moderate or major role, especially among experts with higher levels of experience. This could indicate a shared belief that while the hydrogen economy might be in its early stages now, it has significant potential to grow and become important by 2050.

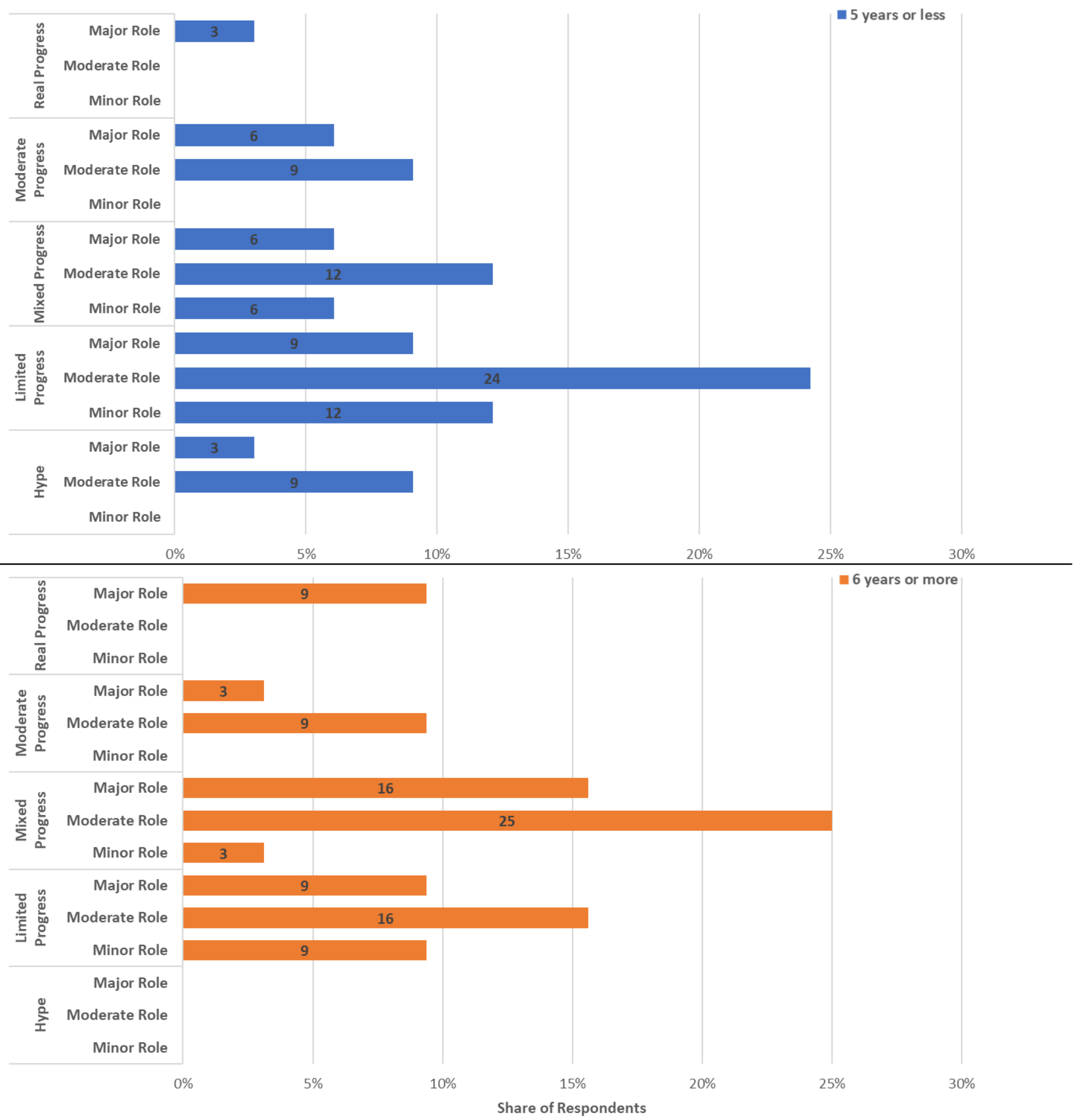

Figure 32: Current progress perspective versus future role of hydrogen and level of hydrogen experience (Top: Experts with 5 years or less experience (n=33) Bottom: Experts with 6 years or more experience (n=32)

None of the experts expect hydrogen to play no role in the future energy landscape (Figure 31). Thus, "No Role" is not indicated in the progress spectrum. Moving from “Hype” to “Real Progress” along the progress spectrum, a clear trend emerges, showing that more experts believe in the hydrogen economy's significant future role. The categories of "Limited Progress" and "Mixed Progress" demonstrate a substantial number of experts envisioning a major or moderate role for hydrogen. This suggests that as the perception of progress grows, so does the optimism for the hydrogen economy's future role. It is also worth noting that the category "Hype," usually associated with inflated expectations, has only four experts (12%) selecting this category. Interestingly, these experts, who have five years or less of experience, seem to perceive that hydrogen's role is significant in the future. A key point from this data is the correlation between the level of expertise and optimism about the future. More experienced experts appear to have a more optimistic view of the hydrogen economy's future role, although it is unclear whether this is an unconscious bias due to long involvement in the sector or a greater depth of insight into the technological progress and transformation that can be translated into long-term potential.

5.3.2 Hydrogen Supply Chain: Trade, Production, Key Role

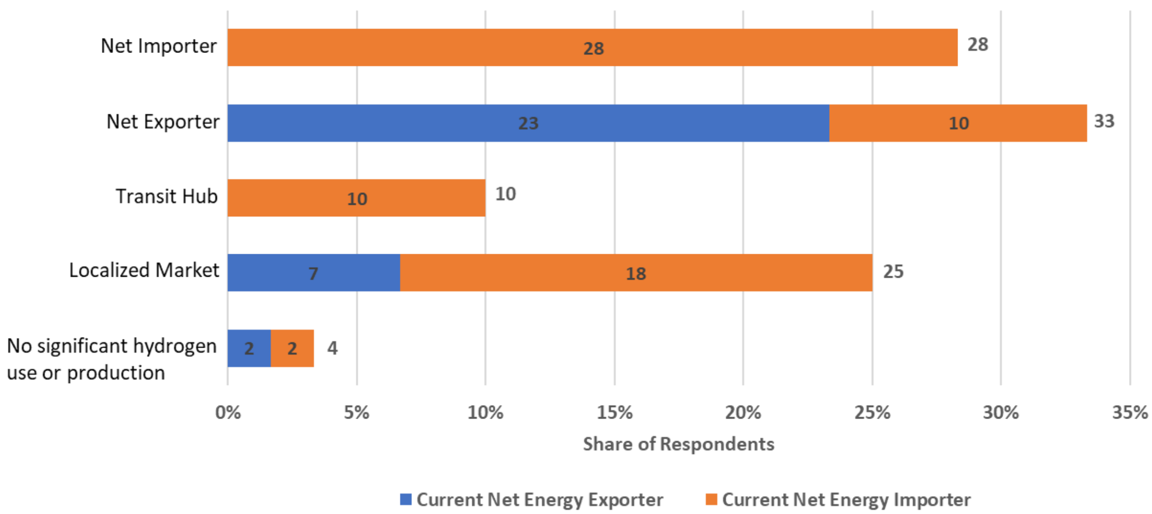

Figure 33: Status of countries as hydrogen develops into an internationally traded commodity (n=60)

Figure 33 presents expert opinions on the potential role of different markets and players as the hydrogen economy develops into an internationally traded commodity. However, five responses were omitted from this result as the experts had selected 'global' in the previous question. The survey categorizes countries into five distinct categories, providing insights into their positions in the hydrogen market. As there are insufficient respondents to analyse the responses on the basis of individual countries, the nations are categorized into net energy exporters and importers based on their total energy self-sufficiency for all energy sources, as derived from the IEA World Energy Balances 2021 [231] for the fiscal year 2020 (see Table 11).

Table 11: Countries` self-sufficiency rate

FY2020	Total self-sufficiency	Coal self-sufficiency	Oil self-sufficiency	Gas self-sufficiency
Algeria	2.28	0	3.06	1.87
Australia	3.46	7.57	0.47	3.36
Belgium	0.27	0.02	0	0
Brazil	1.12	0.15	1.58	0.72
Colombia	2.4	7.73	2.74	0.97
Denmark	0.6	0	0.66	0.56
France	0.55	0	0.01	0
Germany	0.35	0.53	0.03	0.05
Indonesia	1.91	4.33	0.53	1.5
Ireland	0.26	0.13	0	0.36
Italy	0.26	0	0.14	0.06
Japan	0.11	0	0	0.02
Malaysia	1	0.1	0.92	1.58
Peru	1.03	0.17	0.55	1.82
Poland	0.57	0.98	0.03	0.2
Portugal	0.3	0	0	0
Spain	0.32	0	0	0
Thailand	0.5	0.19	0.31	0.63
Turkey	0.3	0.38	0.08	0.01
United Kingdom	0.76	0.2	1.03	0.55
United States	1.06	1.16	1.03	1.1
Vietnam	0.57	0.48	0.39	1

28% of experts anticipate their countries will become net importers of hydrogen. These countries might lack the necessary resources or infrastructure for hydrogen production or might have a high domestic demand that cannot be met by local production alone, thus heavily relying on imports. Notably, each of these countries is already a net energy importer. In contrast, 33% of experts believe that their countries will become net exporters of hydrogen, indicating that these countries might have significant hydrogen production capacities that exceed their domestic consumption, allowing them to export the surplus. Additionally, 10% of experts from current energy importing countries consider that it may be possible for those countries to transition to become net hydrogen exporters. The evolving dynamics of the hydrogen market present an opportunity for nations to reshape their energy portfolios, with potential for strengthening their economies and reducing dependencies on external energy sources (although these policies should be treated with caution [232]).

Only the net energy importing countries seem to serve as transit hubs for hydrogen, with 10% of experts selecting this category. 25% of experts foresee their countries having a localized hydrogen market. Within the current net energy-importing countries, 28% of experts anticipate the emergence of localized hydrogen markets, higher than the 20% within the existing net energy-exporting countries. A small proportion of experts (4%) predict that their countries will have no significant hydrogen use or production.

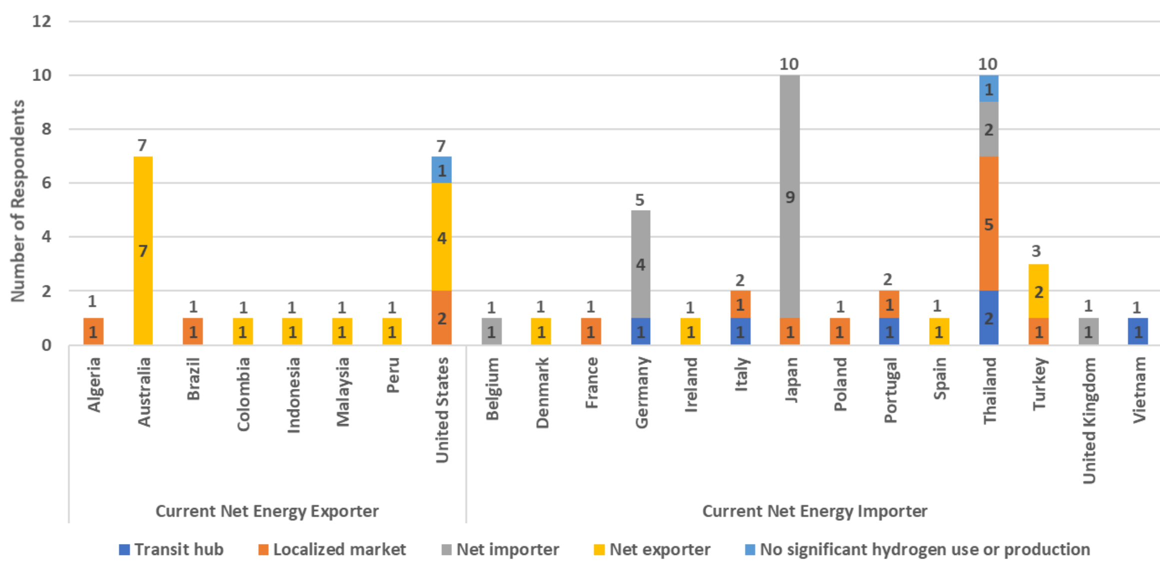

Figure 34: Classification of countries by net energy status in the emerging hydrogen trade (n=60)

Among the nations presented in Figure 34, eight countries, including Algeria, Australia, Brazil, Colombia, Indonesia, Malaysia, Peru, and the United States, are recognized as current net energy exporters. Conversely, fourteen countries, ranging from European nations such as Belgium, Denmark, and Germany to Asian countries like Japan and Thailand, are identified as net energy importers.

All current net exporting countries are anticipated to become net exporters of hydrogen. However, some experts in Algeria, Brazil, and the United States lean towards the development of a localized hydrogen market. In particular, experts in both Australia and Japan are mostly in agreement regarding their nations' future in the hydrogen sector. In Australia, given its abundant resources and established energy export infrastructure, there's a prevailing belief that the country is well-positioned to become a global leader in hydrogen exports. On the other hand, Japan, being an energy-dependent nation with limited natural resources, is looking at hydrogen as a potential alternative to ensure energy security.

Among the current net energy-importing countries, the strategy appears to be diverse. Notably, in countries such as Germany, Italy, Portugal, Thailand, and Vietnam, experts consider their nations as hydrogen transit hubs. Specifically, experts from Denmark, Ireland, Spain, and Turkey are leaning towards exporting hydrogen, despite their countries' current status as net energy importers. On the other hand, experts in France, Italy, Japan, Poland, Portugal, Thailand, and Turkey are advocating for the development of a localized hydrogen market.

Figure 34 suggests the growing importance of hydrogen in the global energy landscape and underscores the strategic positions these countries hold in influencing its future trajectory. However, there is a lack of representative experts for each country, which could potentially lead to gaps in understanding specific regional nuances or may not capture the full spectrum of opinions and strategies in play.

The insights from Figure 33 and Figure 34 are meaningful in understanding the potential dynamics of the emerging global hydrogen economy [233]. It suggests that as hydrogen becomes a globally traded commodity, a new landscape of export-oriented, import-dependent, and transit hub countries may evolve, reminiscent of the current fossil fuel market. However, from the varied expert responses, it is clear that not all nations` prospective status in the global hydrogen market is clear (Figure 34).

Taking real case examples, Brazil and Italy are exploring collaboration on green hydrogen technologies, leveraging Brazil's rich resources and Italy's expertise in industrializing new technologies [234]. The discussions emphasize the opportunity for Brazil to realize its green hydrogen potential through technological cooperation with Italy. Similarly, Australia and Japan are exploring potential pathways for the production and import of hydrogen from Australia for electricity generation [235]. Hydrogen production from Australian brown coal, combined with carbon capture and sequestration (CCS) technology, as well as renewable energy, are being considered.

The diversity of roles also highlights the need for international collaboration in developing global standards and practices for hydrogen production, transportation, and trade [236]. The distribution of roles also has implications for national energy policies. Countries projected to be net exporters should focus on efficient and sustainable hydrogen production technologies, while prospective net importers might need to concentrate on establishing reliable and diverse import sources and strategies. Transit hubs will need to prioritize infrastructure and logistical considerations, and countries with localized markets should balance their domestic production and consumption dynamics.

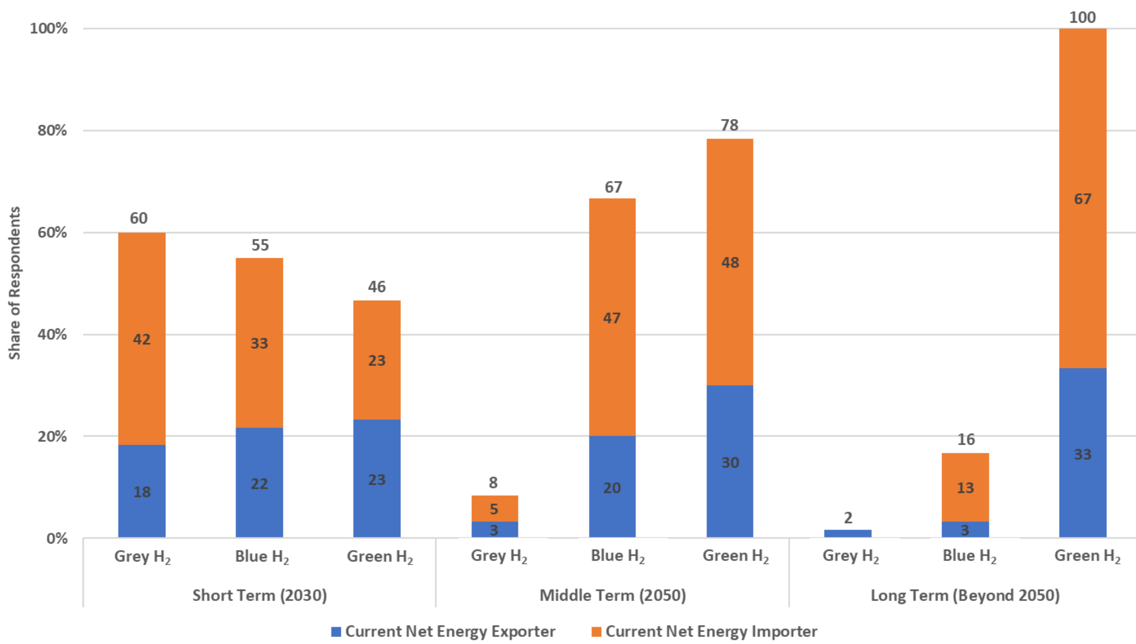

Figure 35: Expected hydrogen production by time horizon and level of hydrogen experience (n=60)

Figure 35 presents expert opinions on the expected methods for hydrogen production across three time periods: short-term (2030), middle-term (2050), and long-term (beyond 2050). It is important to note that these categories are not mutually exclusive, and experts could select multiple production methods for each period.

In the short term (2030), grey hydrogen (produced from fossil fuel via steam methane reforming or gasification, emitting carbon dioxide) was the method expected to be most utilised with 60% of experts selecting it, closely followed by blue hydrogen (grey hydrogen with carbon capture and storage) at 55%. Green hydrogen (produced through electrolysis of water using renewable energy) was selected by 46% of experts, the lowest among the three categories. In the middle term (2050), preferences shift significantly. Only 8% of experts selected grey hydrogen, a substantial drop compared to the short-term. Preference for blue hydrogen rises to 67%, while green hydrogen emerges as the most preferred method, with 78% of experts across all experience levels selecting it. In the long term (beyond 2050), there is a clear consensus among the experts -all experts (100%) selected green hydrogen. Meanwhile, support for grey hydrogen has almost disappeared (2%), and blue hydrogen also sees a significant decline, with only 16% of experts favoring it.

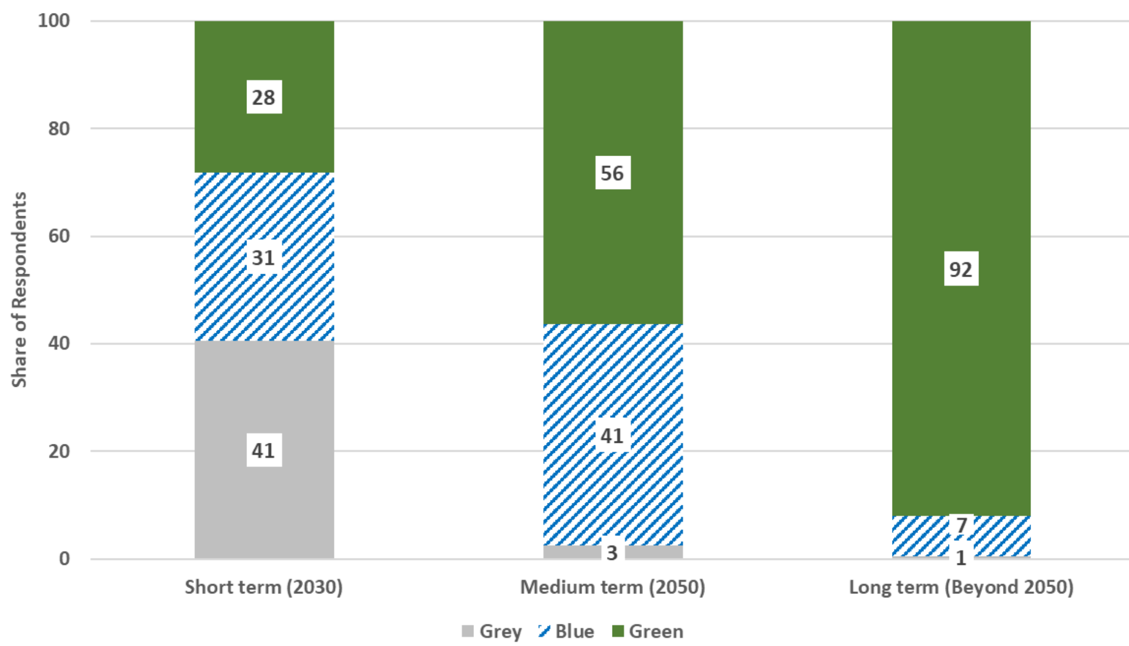

Figure 36: Expected change in hydrogen production (responses fractionally distributed across categories) (n=65)[1]

Figure 36 presents expert opinions on the expected changes in hydrogen production across three timeframes, further highlighting a transition from grey

[1] Experts could select grey, blue and green hydrogen (multiple responses accepted) – each expert`s total response was weighted as 1, with multiple responses distributed across categories (e.g. blue and green selected = 0.5 applied to each category)

to blue, and subsequently to green hydrogen. In the short term, grey hydrogen dominates with 41% of the total weight. Blue and green hydrogen follow closely with 31% and 28%, showing a balance in the short term. This could be considered to reflect a sense of the practicality of using lower cost and established technologies at the present time, in order to support an emerging market for hydrogen, while for many experts carbon-free hydrogen is the only option that can be strategically supported. By the medium term, green hydrogen becomes the leading choice at 56%, while blue hydrogen increases to 41%. Grey hydrogen, which was initially selected, drops to 3%. In the long term, green hydrogen remains dominant at 92%, whereas blue hydrogen's support reduces to 7%. grey hydrogen's significance diminishes further to 1%.

Overall, Figure 35 & Figure 36 implies a transition in the hydrogen production methods over time. Within the responses, there were a number of sub-groups of responses. Six experts considered that only green hydrogen would be utilized, across all timeframes, which might argue that for hydrogen to be worthwhile it must play a role in decarbonization and potentially in facilitating the uptake of renewables through electrolysis. 13 experts considered a step-wise transition – grey hydrogen in the short term, followed by blue, then green. Grey and blue hydrogen, which are currently easier and cheaper to produce but less sustainable relative to green hydrogen [237], may be interpreted as more practical in the short and middle term. However, as technology advances and the urgency to mitigate climate change increases, experts expect a transition towards green hydrogen, the most environmentally friendly among the three but currently more expensive method [238]. This transition should be planned in a way that manages the economic, social, and environmental impacts at each stage, considering factors like employment in the fossil fuel industry, potential technology lock-in of blue hydrogen production infrastructure, the infrastructure needs for green hydrogen, and the global climate targets.

5.3.2.1 Diverse Perspectives on the Future of Hydrogen Production

The landscape of hydrogen production is complex, with disagreements among different stakeholders. Chapter 3 highlights the various stakeholders' preferred methods of hydrogen production, each based on their own perspectives and agendas. Companies in the oil and gas industry have now rebranded themselves as energy companies and are focusing on blue hydrogen production to utilize existing fossil fuel assets during a transitional period toward a cleaner energy future. Environmentalists emphasize green hydrogen production to reduce production costs and address climate change issues. Financial institutions capitalize on the hydrogen economy as new business opportunities, combining economic growth with hydrogen technology.

Chapter 4 introduces another stakeholder group: the broader community. Survey results from the community reveal a divided public opinion between grey and green hydrogen. Even among those who prioritize "adopting cleaner technology" (See Figure 22 and its discussion), a majority still favored grey hydrogen. This suggests that both economic and environmental factors are significant in shaping public decision-making. The option of blue hydrogen (from fossil fuels with CCS) was intentionally omitted from this community survey in order to focus on examining the impact of cost and environmental considerations in hydrogen production.

In Chapter 5, we include an expert survey that provides insights from individuals closely involved in the hydrogen economy. The option of blue hydrogen was included in this chapter, allowing for a more comprehensive comparison of different hydrogen production methods. When considering timeframes, experts foresee a phased transition from grey to blue hydrogen, and eventually to green hydrogen. While grey hydrogen is expected to dominate in the short term, a significant shift toward green hydrogen is anticipated by 2050 and beyond. This projection somewhat aligns with energy companies' views but places greater emphasis on the urgency of transitioning to green hydrogen.

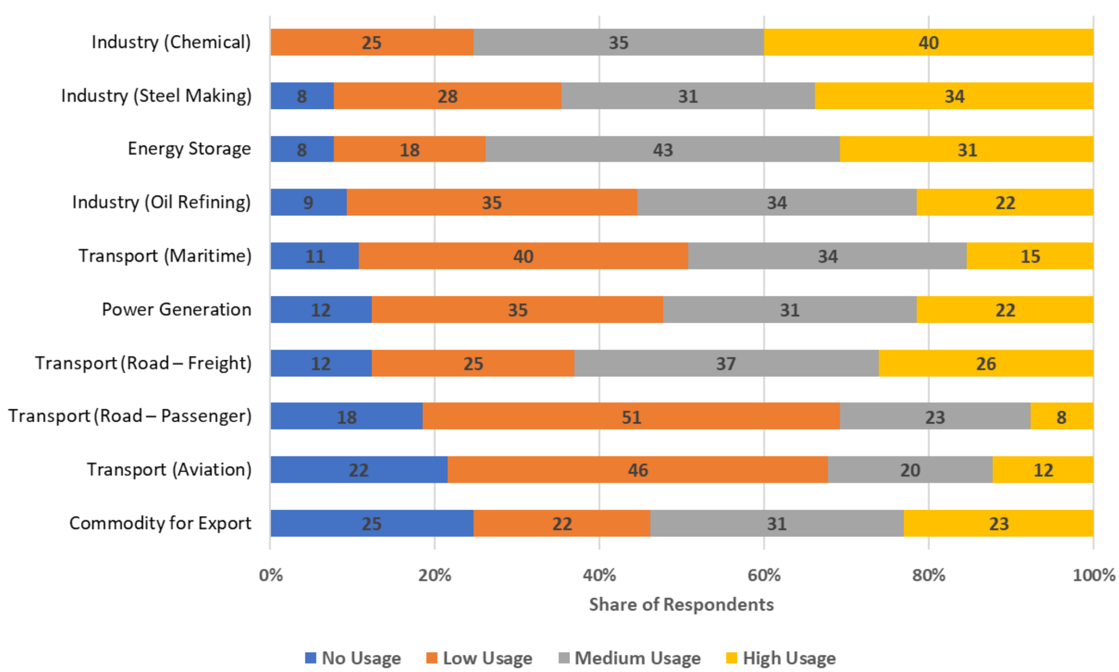

Figure 37: Key sectors in which experts envision hydrogen playing a key role (n=65)

Figure 37 shows the responses regarding key sectors where experts envision hydrogen playing a role, ranging from no usage to high usage.

In terms of "high usage," the chemical industry is perceived to be the leading sector, with 40% of experts expecting a significant role for hydrogen. Hydrogen has long been used in the chemical industry [239], particularly in the production of ammonia for fertilizers and methanol. In the steel-making industry, a comparatively new role for hydrogen is emerging [240], with 34% of experts foreseeing high usage. Steelmaking with hydrogen as a reducing agent can help replace coal in the direct reduction of iron ore. This technology, referred to as direct reduced iron (DRI), is gaining attention due to its potential to significantly reduce the carbon footprint of steel production. Hydrogen has also been used in the oil refining industry for a long time [241]. 56% of experts expect hydrogen to be utilized at medium to high levels in this sector. Specifically within oil refining, hydrogen plays a crucial role in hydrocracking and desulfurization processes. These processes are instrumental in breaking down heavy components of crude oil and eliminating sulfur impurities, resulting in enhanced quality of the end products.

Power generation is another area where hydrogen holds promise. A combined 53% of experts envision medium to high usage of hydrogen, primarily in fuel cells and combustion processes. In fuel cells, hydrogen acts as a fuel source to generate electricity through an electrochemical reaction. This electricity can be used to power various applications, ranging from small portable devices to stationary power systems. For energy storage, 43% of experts predict medium usage, and 31% predict high usage for hydrogen. Hydrogen's capacity to store and generate electricity at a later time positions it as a promising solution for managing surplus power from intermittent renewable energy sources, such as wind and solar.

The transportation sector's expectations for hydrogen usage show significant variation depending on the type of transport. Road freight transport is expected to have the highest hydrogen usage (26%), indicating a strong potential for hydrogen fuel cell vehicles, especially in long-haul transport where batteries may be less effective due to weight and charging time considerations [204]. Conversely, the lowest anticipated use is in passenger road transport (8%), possibly due to the current prevalence and advancing technology of battery-electric vehicles (BEV) [203] and the lack of clear advantages over either BEV or conventional gasoline vehicles, as well as infrastructure impediments. The usage of hydrogen in aviation and maritime transport strikes a balance, reflecting the growing interest in hydrogen as a solution for decarbonizing these sectors, where direct electrification poses significant challenges due to weight and range constraints [204].

As a commodity for export, hydrogen also shows some potential. The majority of experts from current net energy exporting countries (95%) considered that hydrogen would either be used for export (74%) or local markets (21%). Those who considered that there would be net exports of hydrogen from their country mostly expected medium to high usage in exports (63%). Responses were more distributed for experts from current net energy importing countries, although the largest number of experts (around 27%) considered that there would be no usage for exports if the country was a net importer of hydrogen. As countries increase their focus on renewable energy and decarbonization, the export of green hydrogen – produced using renewable energy – may become a significant industry, especially for countries with abundant renewable energy resources [174]. This momentum is reinforced by the consistent decline in solar and wind power costs. Between 2010 and 2019, solar photovoltaics experienced the steepest drop in costs at 82%, followed by concentrated solar power at 47%, onshore wind at 40%, and offshore wind at 29% [174]. Combined into green hydrogen production, this could open new international energy trading relationships and pathways, similar to the role currently played by natural gas and oil.

Figure 37 underscores hydrogen's potential role in decarbonizing various sectors of the economy, particularly in hard-to-abate sectors like chemicals, steelmaking, and freight transport. However, it also highlights that this role might not be equally significant or feasible across all sectors, depending on the specific technological, economic, and logistical challenges involved. Thus, these insights suggest a need for sector-specific strategies [2]. Policies should consider the specific needs and potential of each sector, as well as the timing and sequence of decarbonization efforts. For instance, early efforts might focus on sectors like chemicals or steelmaking where hydrogen usage is expected to be high and where alternative decarbonization options are limited. Meanwhile, in sectors like transport, policies might need to balance the promotion of hydrogen with other technological solutions, such as battery-electric or biofuel technologies. Specifically, the introduction of green hydrogen could serve as a viable solution. The utilization of green hydrogen not only provides an opportunity to significantly reduce their carbon emissions, but also positions these industries at the forefront of sustainable manufacturing. Furthermore, as the role of hydrogen in the export market remains uncertain, policymakers should be cautious about overly relying on hydrogen exports for economic or energy security reasons. They should also actively engage in international collaborations to address the technical and regulatory challenges around hydrogen transportation and trade and to shape the emerging global hydrogen market in a way that aligns with their national interests and capabilities.

5.3.3 Drivers & Barriers for the Implementation of a Hydrogen Economy: A Past and Present Perspective

Figure 38 & Figure 39 illustrate the drivers and the barriers for the development of a hydrogen economy are grouped into five broad categories: political & institutional, environmental, economic, technological, and social. These encompass drivers such as positive public attitudes, technological advancements, financial considerations, environmental impacts, and governmental policies, while also presenting corresponding challenges in the form of barriers to overcome, including public acceptance, technological limitations, financial constraints, environmental concerns, and governance issues. Elaborative descriptions were provided for each category, facilitating a shared understanding for experts in their decision-making processes. Experts ranked the importance of these drivers on a scale ranging from "No Importance" to "High Importance". These categories present a holistic overview of the factors contributing to and impeding the progress of a hydrogen economy. Figure 40 & Figure 41 further delve into expert opinions by comparing past and present drivers and barriers associated with the implementation of a hydrogen economy. Experts had the option to select the past, the present, neither, or both.

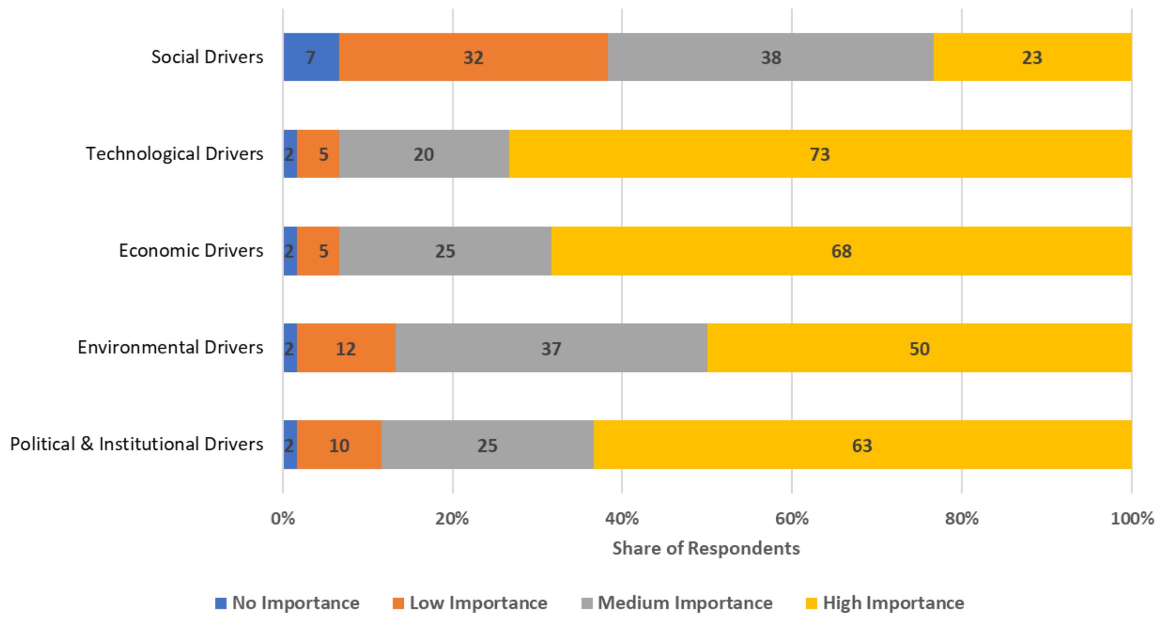

Figure 38: Importance of different drivers for developing a hydrogen economy (n=60)

In Figure 38, the results revealed that technological drivers are seen as the most critical, with 73% of experts marking this driver as of high importance. This underscores the central role of technology in the advancement of the hydrogen economy, with significant advancements required in hydrogen production, storage, distribution, and utilization for it to become a viable energy option. Following closely behind, 68% of experts deemed economic drivers as highly important, reflecting the potential of hydrogen technologies. The ability of hydrogen to compete with other clean technologies and contribute to economic growth and job creation is paramount to its widespread adoption. Political and institutional drivers, marked as highly important by 63% of experts, show the need for supportive government policies and legislation to enable the hydrogen economy. This highlights the importance of political will, strategic planning, and investment in research and development. Environmental drivers were identified as highly important by 50% of experts. While this is lower than other categories, it still indicates significant concern for the environmental impacts and potential benefits of hydrogen technologies, such as reducing greenhouse gas emissions and air pollution. The least prioritized driver was the social aspect, with only 23% of experts marking it as highly important. However, this does not negate its ultimate significance, with social acceptance, understanding, and demand typically considered crucial for the success of any emerging technology [242],

[243]. It may also reflect the distribution of expertise among the experts – this could be further examined with the interview component of the research.

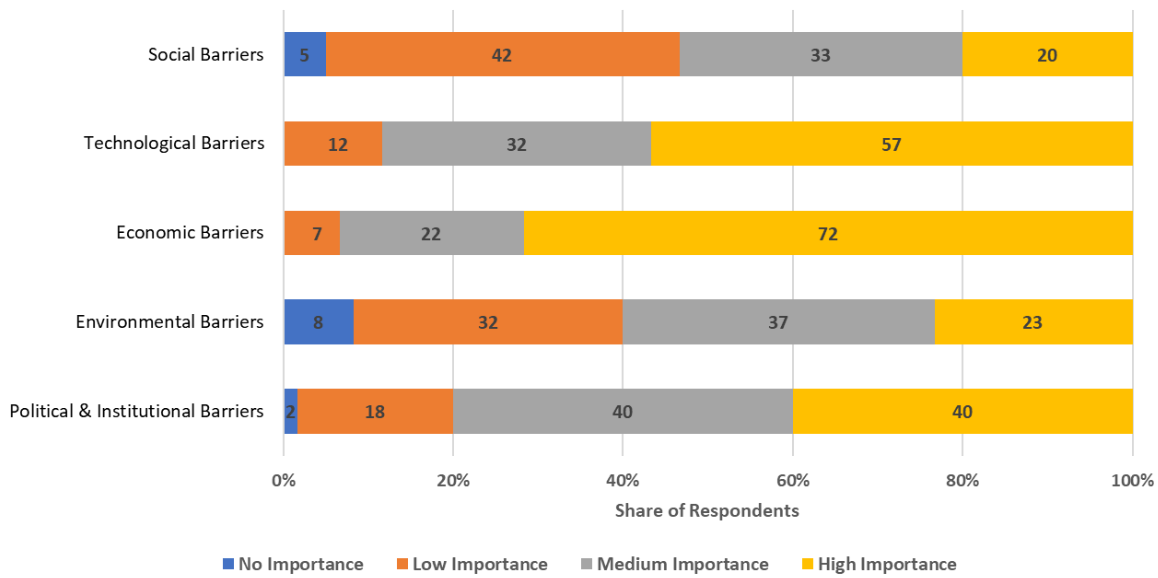

Figure 39: Importance of different barriers for developing hydrogen economy (n=60)

Figure 39 shows that economic barriers are seen as the most significant obstacle to developing a hydrogen economy, with 72% of experts marking them as of high importance. This suggests that high production costs, the lack of a well-established hydrogen market, and the need for significant infrastructure investments are key challenges that need to be addressed for the hydrogen economy to become viable. Technological barriers were considered of high importance by 57% of experts, with issues such as limitations in hydrogen production methods, inefficient storage and transportation infrastructure, and the need for more research and development seen as significant obstacles to the hydrogen economy's development. 40% of experts marked political and institutional barriers as highly important, indicating that the lack of clear policies, inadequate regulatory frameworks, and inconsistent government support are perceived as significant challenges. Environmental barriers were marked as highly important by only 23% of experts, suggesting that concerns about the environmental impact of hydrogen technologies might not be seen as the most pressing challenge, although they still play a role. These concerns include the carbon intensity of hydrogen production methods, unsustainable usage of water for hydrogen production, and the overall life cycle emissions. Lastly, social barriers, including public acceptance, awareness, and attitudes towards hydrogen technologies, were seen as of high importance by just 20% of experts. This suggests that in the same way that social drivers were considered less important, social aspects are currently not seen as a primary barrier to the development of a hydrogen economy.

Technological factors were highlighted as the most significant driver and the second most significant barrier to the development of the hydrogen economy. This demonstrates the pivotal role of technology in the hydrogen economy, but also underlines the challenges that need to be overcome in terms of efficiency and practicality of hydrogen production, storage, and use. The implication here is that stakeholders should invest heavily in technological innovation and research & development to overcome the current challenges. Economic factors, closely ranked to technological factors, are significant both as drivers and barriers. The data shows that while hydrogen's potential for cost competitiveness and economic growth was recognized, the high costs of production, infrastructure, and the lack of a mature hydrogen market are substantial barriers. Thus, the emphasis on economic feasibility is clear, suggesting that policymakers and industry leaders should focus on creating economic incentives, such as tax breaks and subsidies, to stimulate investment and development in this sector.

Political and institutional drivers and barriers are deemed moderately important in both contexts, showing that supportive government policies and clear regulatory frameworks can facilitate the transition to a hydrogen economy. However, the lack of these factors can also pose significant obstacles, pointing towards the need for political commitment and strategic planning. Environmental factors were interestingly ranked lower as both drivers and barriers. This may reflect a perception that the environmental benefits of hydrogen, while important, are secondary to its technological and economic potential. However, it could also indicate a general underestimation of the environmental impacts and challenges associated with hydrogen production and usage. Finally, social factors were perceived as the least important in both contexts. While social acceptance and public awareness are recognized as necessary for the hydrogen economy's success, they are currently not seen as major drivers or barriers. This may suggest a need to increase public education and engagement around hydrogen technologies to ensure their successful integration into society.

Figure 38 & Figure 39 indicated a clear consideration by the majority of experts that technological, economic, and political/institutional factors were more important than environmental and social ones in either blocking or enabling a hydrogen economy. This can inform policymakers and industry leaders about where to focus their efforts. The most effective approach, however, is likely a balanced one that addresses all of these factors. As the hydrogen economy develops, it will be important to consider not just the technical and economic feasibility of hydrogen technologies, but also their environmental impacts, the policies supporting their development, and the social context in which they are introduced. This will require a multi-disciplinary approach, integrating engineering and technology, economics, political science, environmental science, and social science.

Figure 40 presents expert opinions on the comparison of past and present drivers influencing the implementation of a hydrogen economy, spanning a wide array of considerations from environmental concerns to economic aspects and strategic resource management. (See Figure 45 for energy experience)

In all categories, more experts selected the drivers as being currently relevant than in the past. The experts reflected that in the past, "environmental concerns about carbon emissions" were the most prominent driver for implementing a hydrogen economy in both the "5 years or less" and "6 years or more" experience groups, with 61% and 66% selection, respectively. In terms of present drivers, both groups considered "global momentum towards a hydrogen economy" and "utilizing hydrogen as an energy storage solution" as important, while "serving as an energy carrier in sectors difficult to decarbonize" was slightly more important to the more experienced group. "Enhancing energy security", while important to both groups, was seen as more important by the less-experienced group in the present, but more important in the past by the more-experienced. "Reducing dependency on fossil fuels" was also seen as more important in the past by the more-experienced group. The key question is whether these trends are reflective of the changing energy landscape. The concept of a hydrogen economy was initially conceived during a period marked by escalating concerns about the imminent depletion of fossil fuels [6] and increasing pollution levels [7]. Hydrogen was identified as a potential solution to the global energy crisis in the 1970s [135], [136], which encouraged the exploration of alternative technologies. It may be argued that the responses reflect these changing emphases.

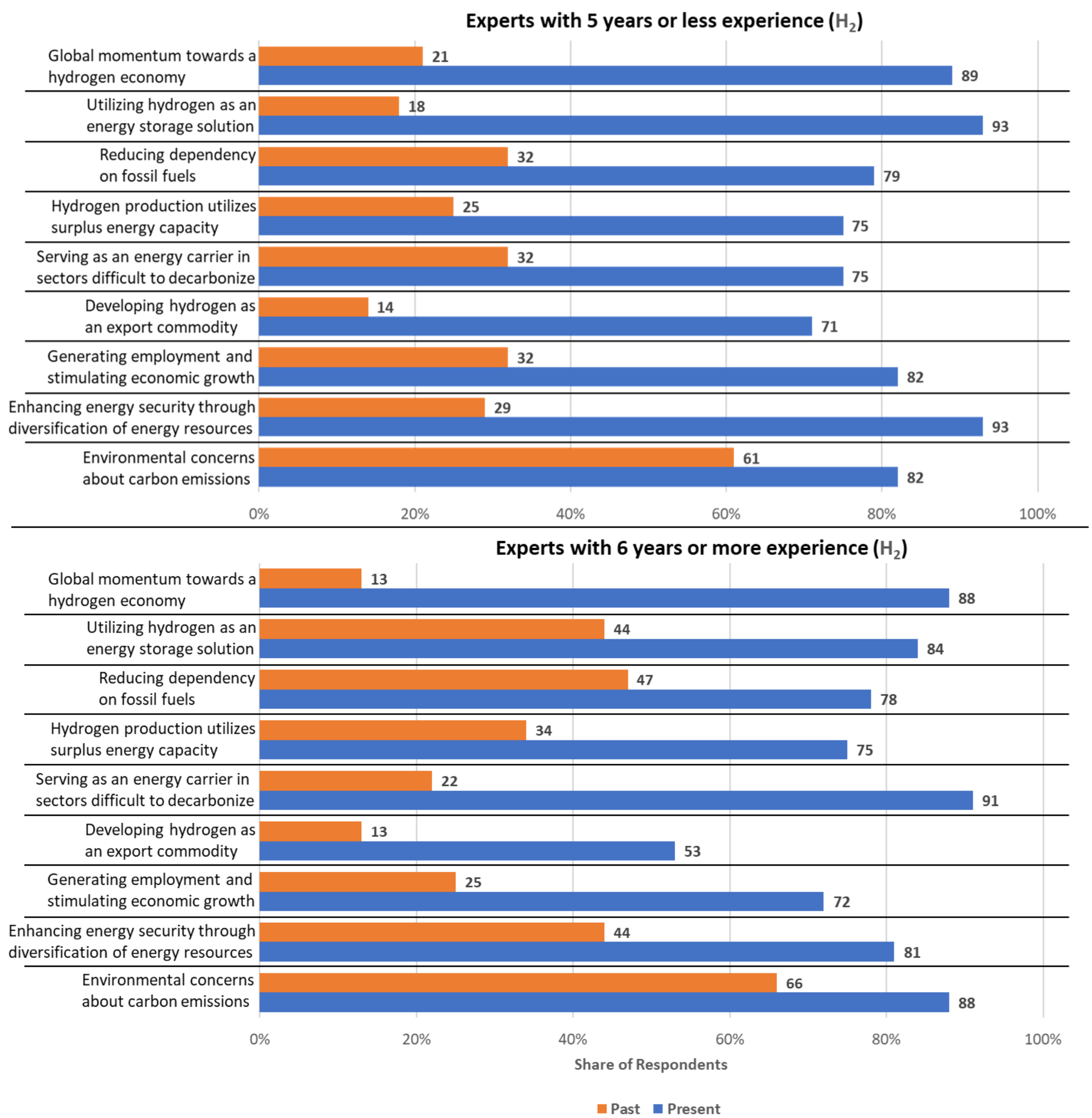

Figure 40: Comparison of past and present drivers for implementing a hydrogen economy (Top: Experts with 5 years or less experience (n=28) Bottom: Experts with 6 years or more experience (n=32))

Two of the most notable increases relate to the drivers of "developing hydrogen as an export commodity" and "global momentum towards a hydrogen economy". This shift underlines a perception of global acceptance and integration of hydrogen into economies as a commodity [233], and a broad-based momentum towards hydrogen solutions [13].

The substantial rise in the perceived importance of these drivers from the past to the present signals a heightened recognition of the multifaceted advantages a hydrogen economy can offer, beyond its mere role as an alternative energy carrier. The perspective on a hydrogen economy has notably evolved over time. While it was once primarily viewed as an environmental solution, it is now recognized for its potential to foster economic growth, enhance energy security, and strategically position economies in the global energy market.

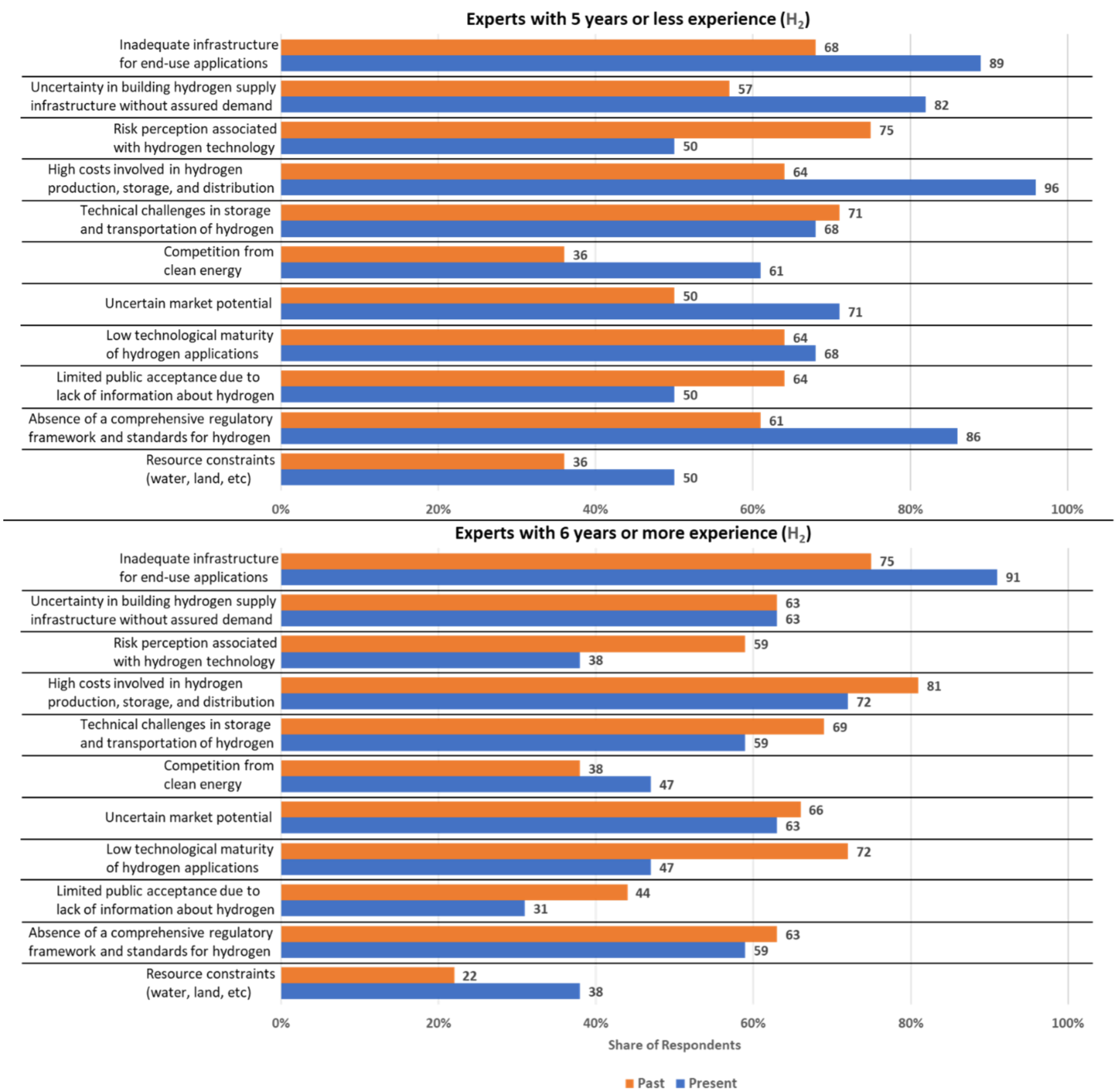

Figure 41: Comparison of past and present barriers for implementing a hydrogen economy (Top: Experts with 5 years or less experience (n=28) Bottom: Experts with 6 years or more experience (n=32))

Figure 41 presents expert opinions comparing the barriers to implementing a hydrogen economy in the past versus the present. The barriers range from resource constraints to technical challenges, economic considerations, and issues with public acceptance and regulatory framework. (See Figure 46 for energy experience) Unlike the drivers, barriers see a more diverse response. “Inadequate infrastructure” was seen as a highly important barrier in both past and present, consistently between both groups of experts. As the potential benefits of a hydrogen economy have become more recognized [13], the absence of necessary infrastructure is becoming more apparent [14], [244], highlighting it as a substantial hurdle in the pathway towards a viable hydrogen economy.

Interestingly, the more-experienced experts` responses indicate a reduction in the importance of cost, technological maturity and lack of regulatory frameworks, whereas the less-experienced group selected these as important now, but not as much in the past. This divergence underscores a contrast in perception. While the less experienced group is becoming increasingly apprehensive about the economic challenges of transitioning to a hydrogen economy, the more-experienced group seems to recognize improvements in cost efficiencies. However, this barrier remains one of the top three obstacles for both groups at present. This reflects the growing recognition of the economic challenges involved in transitioning to a hydrogen economy. It's noteworthy that despite improvements in technology [245] and knowledge about hydrogen [95], the issue of high costs is persistent, indicating that we still have a considerable way to go to make hydrogen an economically viable option for a cleaner future.

The "absence of a comprehensive regulatory framework and standards for hydrogen" stands as the third major barrier at present, with 86% of less experienced experts expressing concern, an increase from their previous perspective of 61%. This underscores the increasing importance that the less experienced group places on the necessity for a robust regulatory framework. However, for the more experienced group, its importance now (59%) is viewed approximately the same as in the past (63%). For this group, the significance of regulatory frameworks and standards for hydrogen remains consistent, reflecting their perception of modest progress in this area.

Both "uncertain market potential" and "uncertainty in building hydrogen supply infrastructure without assured demand" present contrasting perceptions among expert groups based on their experience. "Uncertain market potential" was considered less significant in the past, at 50%, by the less experienced group, but it has increased to 71% in the present. In contrast, the more experienced group shows a slight decrease in their concerns, with a decline from 66% to 63%. The contrast in perception becomes even more pronounced when examining the “uncertainty in building hydrogen supply infrastructure without assured demand". The less experienced group now regards this barrier as more critical, shown by their concerns increasing from 57% to 82%. In comparison, the stance of the more experienced group remains unchanged, consistently at 63%.

Figure 41 illuminates the varied ways in which experts, based on their level of experience, interpret the evolving challenges, and highlight the balance between short-term and long-term progress in the hydrogen sector. While there is much more that could be discussed, in particular it would be useful to understand what time frame is considered “past” by experts, and how this is reflected in their opinions.

5.4 Conclusion

This study employs an expert survey to thoroughly evaluate the hydrogen economy. We start by assessing its current progress and projecting its potential role by the year 2050. The different aspects of the hydrogen supply chain are also explored, with particular focus on trade, production, and key roles within the industry. Lastly, the study analyzes the drivers and barriers for the implementation of a hydrogen economy, providing both past and present perspectives. Notably, it offers a multinational perspective of the hydrogen economy rather than focusing on a single country, an aspect that has yet to be thoroughly explored in previous studies. The results and discussions can be summarized as follows:

- Most experts see only slow progress in the hydrogen economy as of now, but they remain optimistic about the long-term potential of hydrogen in the energy sector by the year 2050.
- As hydrogen becomes a traded commodity, a new landscape of export-oriented, import-dependent, and transit hub countries may evolve,

reminiscent of the current fossil fuel market. Global standards and practices for hydrogen production, transportation, and trade need to be established.

- For the short term, experts hold differing opinions on hydrogen production methods, while a consensus emerges in the middle and long term. The anticipated shift from grey and blue to green hydrogen requires policymakers to adopt a transition strategy that effectively manages economic, social, and environmental impacts at each stage, considering factors like fossil fuel industry employment, potential technology lock-in, green hydrogen infrastructure needs, and global climate targets.
- Given the expected variation in hydrogen usage across different sectors, it is apparent that a one-size-fits-all approach might not work. Policies should be tailored to the specific needs and potential of each sector. Hard to abate sectors, where direct electrification poses significant challenges, should be prioritized.
- Experts prioritize technological, economic, and political factors (drivers and barriers) over environmental and social aspects in the hydrogen economy. However, a balanced approach that considers all these aspects, including the technical and economic feasibility of hydrogen technologies, their environmental impacts, the policies supporting their development, and the social context in which they are introduced, is necessary.
- The significant rise in the perceived importance of drivers over time reflects a growing recognition of the diverse advantages offered by a hydrogen economy, extending beyond its role as a mere environmental solution. It is now acknowledged for its potential to drive economic growth, enhance energy security, and strategically position economies in the global energy market.
- Despite diminishing past barriers like technology maturity, risk perception, and public acceptance, challenges like infrastructure development, regulatory issues, and market uncertainties persist or have grown. Notably, high costs remain a significant barrier, despite advancements in hydrogen technology.

History has witnessed multiple waves of interest in hydrogen without a significant impact. However, the current wave of interest could be different. The urgent global commitment to achieving net-zero emissions by mid-century, and the critical role hydrogen can play in hard to abate sectors, has emerged as a key option for reducing emissions in these areas. This study emphasizes that while hydrogen's contribution to the energy sector has been relatively slow until now, experts predict a significant acceleration driven by strategic decisions and advancements in technology. Acknowledging the complexity of the global hydrogen supply chain, it becomes evident that a standardized framework of international standards and cooperative practices is required, addressing production, trade, and usage in diverse sectors. Additionally, understanding that the shift towards a hydrogen economy requires a multi-dimensional approach, policymakers must balance technological, economic, political, environmental, and social factors to overcome persisting barriers and capitalize on hydrogen's unique potential. The result of this study is expected to create a dialogue that will inform and influence researchers, policy makers, industry stakeholders, and the general public about the potential role and impact of hydrogen in our transition to a more sustainable energy future.

5.4.1 Limitations & Future Work

The current number of experts is sufficient to achieve the objective of showcasing diverse interpretations of hydrogen, while also revealing consensus on certain aspects of hydrogen economy. However, additional respondents are required to obtain a more comprehensive perspective. To gather more data and facilitate ease of response, the survey will remain open and will be translated into different languages. The results will be updated on our laboratory webpage [246] to facilitate the sharing of knowledge.

Among the 65 experts who participated in the survey, 27 of them have agreed to participate in a follow-up interview to discuss more in-depth insights and further expand upon the preliminary findings. The interview will delve into a range of topics that include the technical and economic feasibility of hydrogen production, its potential role in the energy transition, the policy landscape surrounding hydrogen, and the perceived challenges and opportunities in the hydrogen economy. The interview format will also provide an opportunity for a more nuanced discussion, allowing experts to express their thoughts and ideas beyond what can be captured in the survey. The interview responses will be synthesized into a separate paper as the second part of the research, supplementing the survey results and providing a more comprehensive and in-depth understanding of the role of hydrogen in our future energy systems.

Chapter 6 Conclusion & Future Work

6.1 Conclusion

A recurring theme across this study is the interplay of varying perspectives and the need for a multi-stakeholder's approach (Figure 42).

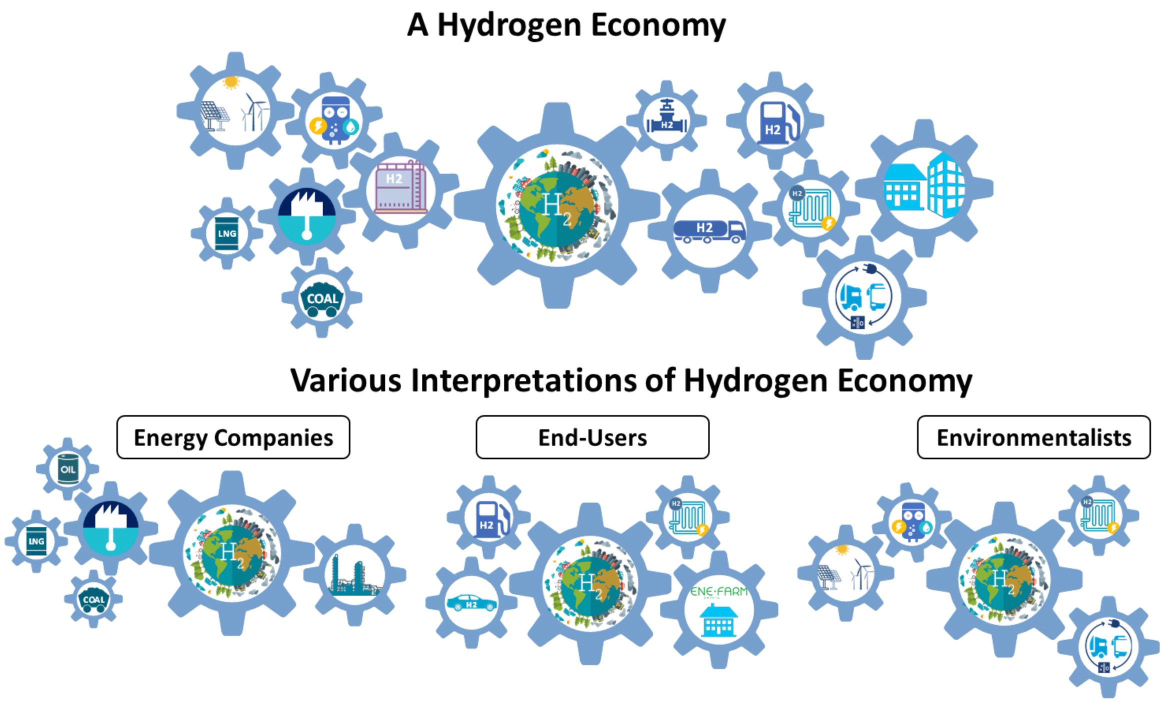

Figure 42: A hydrogen economy and its various interpretations

The implementation of a functional hydrogen economy lies not only in its technical feasibility or economic viability but also in its societal acceptance. No matter how technologically advanced or economically viable hydrogen becomes as an energy carrier, its widespread integration could falter if stakeholders remain skeptical or resistant. Moreover, the public's perception has a significant ripple effect on policy-making and regulations. A society that's enthusiastic and well-informed about hydrogen's potential can drive political agendas, leading to favorable policies, incentives, and encouraging regulatory landscapes. On the other end, experts play a pivotal role in the broader narrative of the hydrogen economy. They help shape public understanding, influence media portrayals, and even inform policy making about hydrogen technologies and their implications. Therefore, their voice is instrumental in crafting a coherent, informed, and forward-looking narrative around the hydrogen economy.

Despite the general positivity towards hydrogen, public perceptions in Japan underscore a disconnect between perceived and actual understanding, emphasizing the need for transparent communication. Experts' views reveal an evolving recognition of the hydrogen economy's multifaceted benefits and a shift in perceived challenges, spotlighting the need for comprehensive regulation, robust infrastructure, and competitiveness against other clean technologies. The main findings are summarized as follows:

1. **Hype Cycles and Various Interpretations of the Hydrogen Economy Development**

Historical analysis elucidated the chronological narrative of the hydrogen economy, mapping it against significant events. This history has underscored the importance of recognizing hype cycles as integral to technological evolution, shaped by specific events and influenced by competing actors with diverse agendas. While there are differing perspectives and interpretations among actors, this has created somewhat of a shared concept of the hydrogen economy which is flexibly interpreted as to what a future hydrogen economy may look like. Assessing the current perspectives of stakeholders on a hydrogen economy is important to understanding social support and aligning our expectations of the hydrogen economy.

2. **Societal Perceptions and the Hydrogen Economy**

From the Japanese context, public attitudes suggest both a knowledge gap and a degree of optimism. While there is a recognized disconnect between self-perceived and objective understanding of hydrogen technologies, the community's acceptance towards hydrogen-based applications, especially in the transportation sector, is positive. However, the public's perception of hydrogen production and utilization diverges from reality, which emphasizes the need for effective and clear communication to align public perception with reality. The recent survey's neutral public response suggests an opportunity to enhance engagement and foster informed support for the hydrogen economy through targeted education and transparent information dissemination. Policymakers should build upon this foundation, directing efforts toward bridging knowledge gaps by leveraging preferred communication mediums.

3. **Expert Opinions on the Hydrogen Future**

Expert opinions project a cautiously optimistic future. While the current progress of the hydrogen economy might appear slow, its future role, especially by 2050, is significant. However, this potential is riddled with challenges, ranging from establishing global standards for production and trade to navigating economic, technological, and environmental hurdles. Yet, there is a growing recognition of the multi-dimensional benefits that a hydrogen economy can offer, extending beyond its initial promise as an environmental solution. These benefits include fostering economic growth, enhancing energy security, and strategically positioning economies in the global energy landscape. The decrease in perceived significance of certain barriers is encouraging, signaling progress in public understanding, technology maturation, and reduced risk perceptions. Nevertheless, new challenges have emerged, highlighting the need for comprehensive regulatory frameworks, development of end-use infrastructure, and the ability to compete with other clean energy technologies.

In conclusion, this study provides empirical evidence to support the "false start" notion posited by the IEA [1], as well as IRENA's observation that "Hydrogen has spurred multiple waves of interest in the past without significant impact" [2]. By analyzing annual academic publications, mass media articles, and hydrogen-related projects from 1972 to 2020, the study illustrates the cyclical pattern of rising and falling interest, thereby validating the existence of hype cycles in the development of the hydrogen economy. From an expert perspective, while the majority perceive limited progress in the development of the hydrogen economy, they remain optimistic about its long-term potential, particularly by 2050. This optimism is mirrored in the Japanese community, which has shown a growth in public awareness of hydrogen energy from 2008 to 2022.

The novel contributions of this thesis lie in its multi-stakeholder perspective, temporal focus, and a series of studies that consider various types of data (retrospective publications, community and expert opinions) in the development of the hydrogen economy. Unlike existing studies, this research uniquely integrates a historical overview, as presented in Chapter 3, dating back to the inception of the hydrogen economy in 1972, with contemporary primary data from both community and expert surveys covered in Chapters 4 and 5. This synthesis provides a nuanced understanding of how public and expert opinions have evolved over time, set within a broader historical context. Moreover, the thesis adopts a holistic systems perspective to comprehensively evaluate the entire hydrogen supply chain, from production to distribution, offering intricate details about its development and implementation. Lastly, the study serves as a real-time snapshot of current perspectives, laying the groundwork for future academic inquiries, policymaking, and industry strategies. This multi-pronged approach not only fills a gap in the existing literature but also yields valuable insights that can significantly inform future policy decisions, industry initiatives, and research directions in the development of the hydrogen economy.

6.2 Future Work

Building on the findings of the present study, several avenues for future research are proposed to further deepen the understanding of the social dimensions of the hydrogen economy:

- **Quantitative Analysis**: To complement the qualitative insights, quantitative studies leveraging explanation-focused analyses like regression models can be undertaken. By adopting this approach, we can more accurately measure the influence of different factors on the acceptance of the hydrogen economy and provide a clearer representation of hydrogen's social evolution over time. Even though certain aspects like the acceptance of fuel cell vehicles and refueling stations have been studied, the broader acceptance of the hydrogen economy, particularly from a systems perspective (from production to distribution), remains an untapped area of research.

- **Increased Sample Size**: While the number of experts in this study provided valuable insights, a larger sample size would further enhance the robustness of the findings. Hence, the ongoing survey will remain accessible and will be translated into multiple languages to invite a broader spectrum of responses. Continuous updates will be provided on the laboratory webpage, promoting more extensive knowledge sharing.

- **Follow-up Interviews with Experts**: The follow-up interviews with the 27 experts who consented are to be conducted soon. This phase will not only supplement the preliminary survey findings but also delve deeper into intricate subjects like hydrogen production feasibility, its role in the energy transition, policy implications, and perceived challenges and opportunities. Capturing the insights from these interviews is expected to contribute significantly to the academic discourse on the topic.

The present study serves as a foundational step towards understanding the evolving perspective on the hydrogen economy. The potential avenues highlighted for future research aim to further clarify and enrich the topic, ensuring that it is examined comprehensively from both qualitative and quantitative perspectives.

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Appendices

Appendix A. Supplement Data for Bibliometric Analysis

Table 12: Search query for SCOPUS and LEXIS database

SCOPUS Search Query
TITLE ((“Hydrogen” “Economy”) OR (“Hydrogen” “Society”) OR (“Hydrogen” “Roadmap”) OR (“Hydrogen” “Future”) OR (“Hydrogen” “Energy Carrier”) OR (“Hydrogen” “Energy Source”) OR (“Hydrogen” “Energy System”))
Related Figure: Figure 11
SCOPUS Search Query
TITLE ((“electric vehicle”) AND NOT (“fuel cell”))
Related Figure: Figure 12a
SCOPUS Search Query
TITLE ((“fuel cell vehicle” OR “fuel cell electric vehicle”))
Related Figure: Figure 12b
LEXIS Search Query
(“Hydrogen Economy”) OR (“Hydrogen Society”) OR (“Hydrogen Roadmap”) OR (“Hydrogen Future”) OR (“Hydrogen Energy Carrier”) OR (“Hydrogen Energy Source”) OR (“Hydrogen Energy System”)
Related Figure: Figure 11
LEXIS Search Query
(“electric vehicle”) AND NOT (“fuel cell”)
Related Figure: Figure 12a
LEXIS Search Query
(“fuel cell vehicle” OR “fuel cell electric vehicle”)
Related Figure: Figure 12b

Table 13: Summary of keyword co-occurrence analysis

Time Period	No. of Paper	Total Keywords	Total Unique Keywords	Related Figure
1972–1979	45	83	24	Figure 6
1980–1989	25	78	27	Figure 7
1990–1999	14	113	54	Figure 8
2000–2009	251	2317	122	Figure 9
2010–2019	174	2072	124	Figure 10

Topical Theme	Keywords					
Actor	aerospace industry	agricultural industry	asia	automobile industry	chemical industry	developing country
	energy industry	europe	iea	industrial	international	user
Environmental Issue	atmosphere	cabon dioxide	climate change	decarbonizatio n	disaster	environment
	environment al impact	environment al quality	global warming	pollution		
Economy / Market	commerce	competition	cost	cost effectiveness	economic barrier	economic impact
	economics	economy	energy economy	fuel economy	investment	marketing
Fossil Fuel Technology	coal	combustion	fossil fuel	internal combustion engine	methane	natural gas
	petroleum	steam reforming				
Energy	electricity	energy	energy carrier	energy resource	fuel	primary energy
Energy / Clean Technology	alternative energy	bio-energy	biomass	clean energy	hydropower	nuclear energy
	renewable energy	solar energy	wind energy			
Clean Technology	battery	catalysis	ccs	decentralized	distributed energy system	electric vehicle
	hybrid car	photovoltaic	power to gas			
Hydrogen Economy	electrolysis	fuel cell	fuel cell vechile	hydride	hydrogen technology	metal hydride
	hydrogen	hydrogen economy	hydrogen energy	hydrogen fuel		
	hydrogen energy system	hydrogen infrastructur e	hydrogen production	hydrogen storage		
Planning & Policy	decision making	energy conservation	energy conversion	energy demand	energy efficiency	energy management
	energy mix	energy policy	energy security	energy storage	energy system	energy utilization
	infrastructur e	policy	power system	public acceptance	roadmap	socio aspect
	supply chain	supply demand	sustainable developme nt	technical challenge	transition	transportation
Research & Development	economic analysis	economic and social analysis	risk analysis	socio-economy	socio technical	techno-economic
	gis	life cycle assessment	optimizatio n	research	safety measure	simulation

Figure 43: Topical themes and specific keywords in keyword co-occurrence analysis

Appendix B. Supplementary Data for Expert Survey Analysis

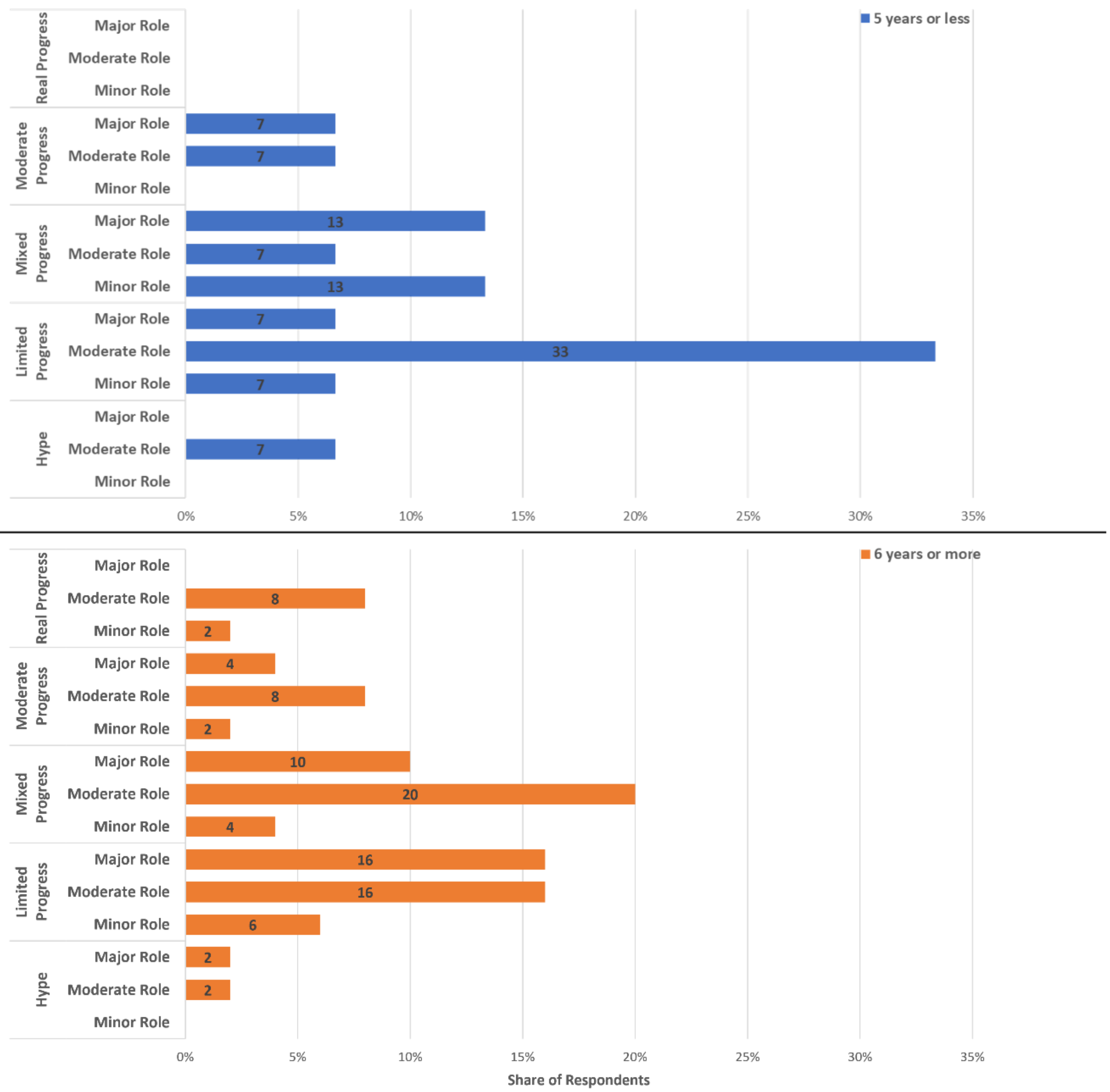


Figure 44: Current progress perspective versus future role of hydrogen and level of energy experience (Top: Experts with 5 years or less experience (n=15) Bottom: Experts with 6 years or more experience (n=50)

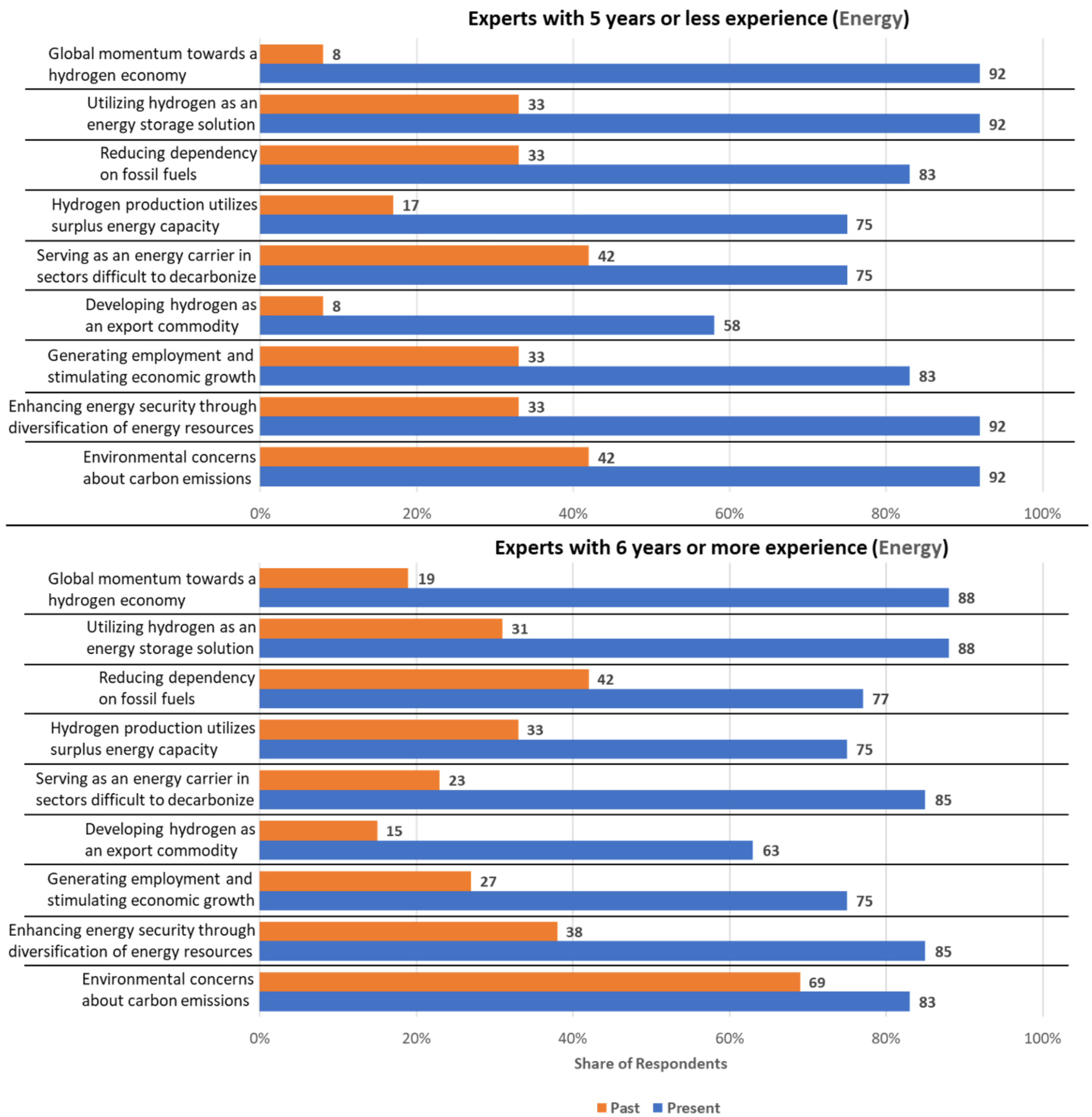


Figure 45: Comparison of past and present drivers for implementing a hydrogen economy (Top: Experts with 5 years or less experience (n=12) Bottom: Experts with 6 years or more experience (n=48))

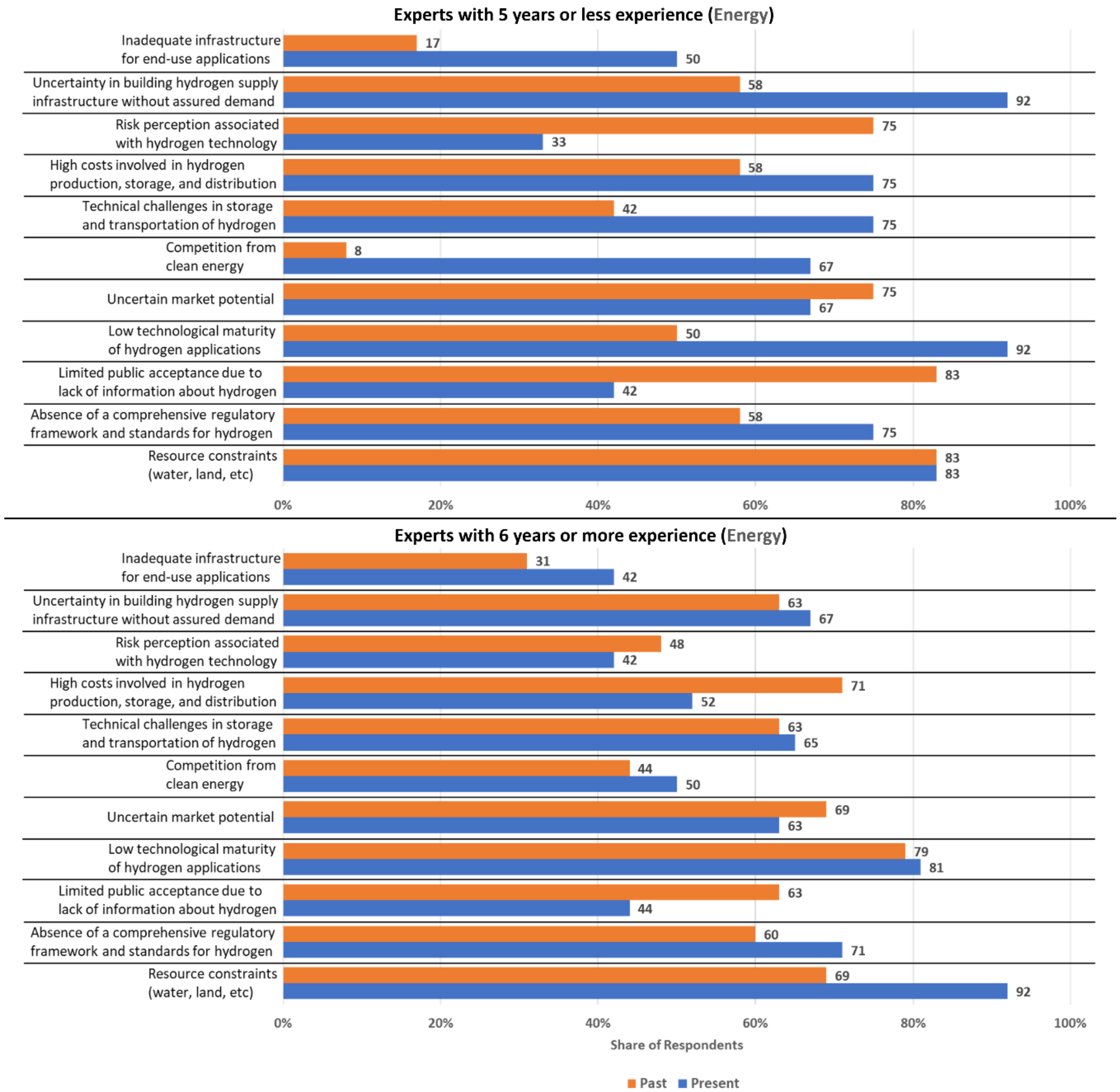


Figure 46: Comparison of past and present barriers for implementing a hydrogen economy (Top: Experts with 5 years or less experience (n=12) Bottom: Experts with 6 years or more experience (n=48))

Appendix C. Public Survey Questionnaire

Q1　次のエネルギー・技術をご存知ですか？それぞれについて、いずれか1つお選びください。

		よく知っている	だいたい知っている	聞いたことがある	聞いたことがない
Q1A1*	化石燃料	○	○	○	○
Q1A2*	原子力	○	○	○	○
Q1A3*	太陽エネルギー（太陽光、太陽熱）	○	○	○	○
Q1A4*	水素エネルギー (水素自動車)	○	○	○	○
Q1A5*	風力	○	○	○	○
Q1A6*	バイオマスエネルギー	○	○	○	○
Q1A7*	地熱	○	○	○	○
Q1A8*	波力	○	○	○	○
Q1A9	水力	○	○	○	○
Q1A10	二酸化炭素回収・貯留 (CCS)	○	○	○	○

※化石燃料は石炭、天然ガス、石油など

Q2　あなたは「エネルギー・技術」に関する情報を何で知りましたか？以下の選択肢より最も当てはまるものを3つまでお選びください。

Q2A1	テレビ	○
Q2A2	SNS (Facebook・LINE・Twitterな	○
Q2A3	インターネット	○
Q2A4	新聞	○
Q2A5	社会実証プロジェクト	○
Q2A6	見学 (展示会・科学館)	○
Q2A7	雑誌・本	○
Q2A8	行政文書	○
Q2A9	学校/大学 (講演会・論文)	○
Q2A10	知人などに教えてもらった	○

Q3 **の水素技術をご存知ですか？それぞれについて、いずれか 1 つお選びください。**

		よく知っている	だいたい知っている	聞いたことがある	聞いたことがない
Q3A1	水蒸気改質 (水素生産)	○	○	○	○
Q3A2	水電解 (水素生産)	○	○	○	○
Q3A3	ガス化 (水素生産)	○	○	○	○
Q3A4	圧縮水素 (水素貯蔵)	○	○	○	○
Q3A5	液体水素 (水素貯蔵)	○	○	○	○
Q3A6	水素吸蔵合金 (水素貯蔵)	○	○	○	○
Q3A7	水素車・水素バス (水素用途)	○	○	○	○
Q3A8	エネファーム (水素用途)	○	○	○	○
Q3A9	産業用途 (水素用途)	○	○	○	○

※産業用途は石油精製、製鉄、アンモニア製造など。

Q4 **あなたは次の政策や協定等について知っていますか？それぞれについて、いずれか 1 つお選びください。**

		よく知っている	だいたい知っている	聞いたことがある	聞いたことがない
Q4A1	パリ協定	○	○	○	○
Q4A2	エネルギー基本計画 (日本)	○	○	○	○
Q4A3	国別約束草案（INDC）	○	○	○	○
Q4A4	固定価格買取制度（FIT）	○	○	○	○
Q4A5	水素・燃料電池戦略ロードマップ (日本)	○	○	○	○
Q4A6	都道府県内のエネルギー割合：現状と目標	○	○	○	○
Q4A7	締約国会議（COP）	○	○	○	○
Q4A8	京都議定書	○	○	○	○
Q4A9	気候変動に関する政府間パネル（IPCC）	○	○	○	○
Q4A10	持続可能な開発目標 (SDGs)	○	○	○	○
Q4A11	水素利用国際クリーンエネルギーシステム技術 (WE-NET)	○	○	○	○

Q5　あなたにとって最も重要なSDGsの目標を3つ、重要と思う順番にお選びください。
※以下URLをご覧になってからご回答ください。
https://www.jp.undp.org/content/tokyo/ja/home/sustainable-development-goals.html

		1位/番目	2位/番目	3位/番目
Q5A1	**貧困をなくそう** あらゆる場所あらゆる形態の貧困を終わらせる	○	○	○
Q5A2	**飢餓をゼロに** 飢餓を終わらせ、持続可能な農業を促進する	○	○	○
Q5A3	**気候変動に具体的な対策を** 気候変動及びその影響を軽減するための緊急対策を講じる	○	○	○
Q5A4	**質の高い教育をみんなに** 包摂的かつ公正な質の高い教育を確保する	○	○	○
Q5A5	**働きがいも経済成長も** 包摂的かつ持続可能な経済成長とすべての人々の生産的な雇用を促進する	○	○	○
Q5A6	**陸の豊かさも守ろう** 陸域生態系の保護、持続可能な森林の経営、生物多様性の損失を阻止する	○	○	○
Q5A7	**エネルギーをみんなに。そしてクリーンに** 安価かつ信頼できる持続可能な近代的なエネルギーへのアクセスを確保する	○	○	○
Q5A8	**すべての人に健康と福祉を** すべての人々の健康的な生活を確保し、福祉を促進する	○	○	○
Q5A9	**つくる責任、つかう責任** 持続可能な消費生産形態を確保する	○	○	○
Q5A10	**ジェンダー平等を実現しよう** ジェンダー平等を達成し、すべての女性のエンパワーメントを行う	○	○	○
Q5A11	**人や国の不平等をなくそう** 国内及び各国家間の不平等を是正する	○	○	○
Q5A12	**安全な水とトイレを世界中に** すべての人々の水と衛生の利用可能性を確保する	○	○	○
Q5A13	**海の豊かさを守ろう** 持続可能な開発のために、海洋・海洋資源を保全し、持続可能な形で利用する	○	○	○
Q5A14	**平和と公正をすべての人に** 開発のための平和で包摂的な社会を促進し、司法へのアクセスを提供する	○	○	○

Q6　あなたにとって政府に最優先に取り組んで欲しいエネルギー問題を3つ、重要と思う順番にお選びください。

		1位/番目	2位/番目	3位/番目
Q6A1	化石燃料への依存度を低減する	○	○	○
Q6A2	エネルギー資源の輸入を削減する	○	○	○
Q6A3	よりクリーンな技術の採用	○	○	○
Q6A4	エネルギーコストの削減	○	○	○
Q6A5	エネルギーの安定供給の確保	○	○	○
Q6A6	原子力発電所の安全の確保	○	○	○
Q6A7	すべてのステークホルダー（エネルギー生産者と消費者）にと	○	○	○

Q7 現在の日本の **CO2** 排出量削減目標は、以下のどれに当てはまると思いますか？それぞれについて、いずれか **1** つお選びください。

		2013年度比26%CO2削減	2013年度比36%CO2削減	2013年度比46%CO2削減	2013年度比50%CO2削減	2013年度比80%CO2削減	ネットゼロ（CO2排出ゼロ）	わからない
Q7A1	2030年度までに (2021年発表)	○	○	○	○	○	○	○
Q7A2	2050年度までに (2020年発表)	○	○	○	○	○	○	○

Q8 以下は水素エネルギーについての意見です。あなたはどのように思いますか？それぞれについて、いずれか **1** つお選びください。

		そう思わない	あまり思わない	どちらともいえない	少し思う	そう思う
Q8A1*	水素エネルギーの利用を進めれば、化石燃料に頼らないですむようになる	○	○	○	○	○
Q8A2*	水素エネルギーの利用を進めれば、地球温暖化、大気汚染を解決できる	○	○	○	○	○
Q8A3*	水素は一般の人々が日常生活において使用するには危険である	○	○	○	○	○
Q8A4	水素エネルギーの利用を進めれば、国内経済を活性化することができる	○	○	○	○	○
Q8A5	水素技術は現時点では高価である	○	○	○	○	○

※水素インフラは水素ステーション、水素パイプライン、水素貯蔵タンク
※水素技術は水素車、水素バス、エネファーム

Q9　それぞれのエネルギー・技術の増加・減少について、あなたの考えを以下のそれぞれについて1つお選びください。

		激減させるべき	減らすべき	どちらでもない	増やすべき	激増させるべき	わからない
Q9A1	石炭(CCSなし)	○	○	○	○	○	○
Q9A2	石炭(CCSあり)	○	○	○	○	○	○
Q9A3	天然ガス(CCSなし)	○	○	○	○	○	○
Q9A4	天然ガス(CCSあり)	○	○	○	○	○	○
Q9A5	バイオマスエネルギー (CCSなし	○	○	○	○	○	○
Q9A6	バイオマスエネルギー(CCSあり)	○	○	○	○	○	○
Q9A7	原子力	○	○	○	○	○	○
Q9A8	太陽エネルギー	○	○	○	○	○	○
Q9A9	水素エネルギー	○	○	○	○	○	○
Q9A10	水力	○	○	○	○	○	○
Q9A11	風力	○	○	○	○	○	○
Q9A12	石油	○	○	○	○	○	○
Q9A13	地熱	○	○	○	○	○	○

※CCSは二酸化炭素回収・貯留

Q10a 各エネルギー源の現状維持・増やすべき・激増させるべきを希望する理由を下記の中からそれぞれお選びください。（いくつでも）

		安全・安心	自然エネルギーである	環境への配慮	安定供給のため	二酸化炭素排出量が少ない	費用が安い	資源の有効活用	代替がない	よくわからない
Q10A1	石炭(CCSなし)	○	○	○	○	○	○	○	○	○
Q10A2	石炭(CCSあり)	○	○	○	○	○	○	○	○	○
Q10A3	天然ガス(CCSなし)	○	○	○	○	○	○	○	○	○
Q10A4	天然ガス(CCSあり)	○	○	○	○	○	○	○	○	○
Q10A5	バイオマスエネルギー (CCSなし	○	○	○	○	○	○	○	○	○
Q10A6	バイオマスエネルギー(CCSあり)	○	○	○	○	○	○	○	○	○
Q10A7	原子力	○	○	○	○	○	○	○	○	○
Q10A8	太陽エネルギー	○	○	○	○	○	○	○	○	○
Q10A9	水素エネルギー	○	○	○	○	○	○	○	○	○
Q10A10	水力	○	○	○	○	○	○	○	○	○
Q10A11	風力	○	○	○	○	○	○	○	○	○
Q10A12	石油	○	○	○	○	○	○	○	○	○
Q10A13	地熱	○	○	○	○	○	○	○	○	○

Q10b 各エネルギー源の減らすべき・激減させるべきを希望する理由を下記の中からそれぞれお選びください。（いくつでも）

		危険	環境への悪影響	発電が不安定	二酸化炭素排出量が多い	費用が高い	資源の枯渇性	必要がない	よくわからない
Q10A1	石炭(CCSなし)	○	○	○	○	○	○	○	○
Q10A2	石炭(CCSあり)	○	○	○	○	○	○	○	○
Q10A3	天然ガス(CCSなし)	○	○	○	○	○	○	○	○
Q10A4	天然ガス(CCSあり)	○	○	○	○	○	○	○	○
Q10A5	バイオマスエネルギー (CCSなし	○	○	○	○	○	○	○	○
Q10A6	バイオマスエネルギー(CCSあり)	○	○	○	○	○	○	○	○
Q10A7	原子力	○	○	○	○	○	○	○	○
Q10A8	太陽エネルギー	○	○	○	○	○	○	○	○
Q10A9	水素エネルギー	○	○	○	○	○	○	○	○
Q10A10	水力	○	○	○	○	○	○	○	○
Q10A11	風力	○	○	○	○	○	○	○	○
Q10A12	石油	○	○	○	○	○	○	○	○
Q10A13	地熱	○	○	○	○	○	○	○	○

Q11 日本のエネルギーミックスとして、何が最適だと思いますか？
※合計 **100%**になるように半角で数値を入力してください
※エネルギーミックスとは、化石燃料、原子力、自然エネルギーなど、さまざまな方法を組み合わせて発電することです

		割合回答	
Q11A1	自然エネルギー		※太陽エネルギー、風力 、水力など
Q11A2	原子力		
Q11A3	化石燃料		※石炭、天然ガス、石油など

Q12 あなたは次のような条件のもと、日本が水素の輸入に頼るべきだと思いますか？その場合以下のどの水素に頼ればいいと思いますか？それぞれについて、いずれか **1** つお選びください

		海外からあらゆる種類の水素を輸入	海外からクリーン水素を輸入する	海外から水素を輸入しない
Q12A1	日本国内では水素を生産できない場合は	○	○	○
Q12A2	日本国内ではクリーンな水素を生産できない場合は	○	○	○
Q12A3	国内で水素を生産するよりも輸入した方が安い場合は	○	○	○

※クリーン水素はCO2の排出ゼロ

Q13 水素社会を実現するために、まずは、以下のどちらの方法で水素を生産すべきだと思いますか？

Q13A1	高価な低CO2排出の水素	○
Q13A2	安価な高CO2排出の水素	○

Q14 以下の水素の性質について、正しいと思う選択肢をそれぞれについて、いずれか **1** つお選びください。

		正しい	正しくない	わからない
Q14A1*	水素は有毒である	○	○	○
Q14A2*	水素はにおいがない	○	○	○
Q14A3*	水素はある条件で爆発することがある	○	○	○
Q14A4*	水素はエネルギー資源である	○	○	○
Q14A5*	水素は空気より軽い	○	○	○

Q15　水素自動車について、正しいと思う選択肢をそれぞれについて、いずれか1つお選びください。

		正しい	正しくない	わからない
Q15A1*	水素自動車は水素を燃焼させることで走る	○	○	○
Q15A2	水素自動車の副産物は水と熱である	○	○	○

Q16　現在、水素の製造方法として最も多いと思うものを3つお選びください。

Q16A1	天然ガス	○
Q16A2	原子力	○
Q16A3	石炭	○
Q16A4	大気から集める	○
Q16A5	電気で水電解 (自然エネルギーで発電)	○
Q16A6	電気で水電解 (化石燃料で発電)	○
Q16A7	石油	○
Q16A8	バイオマス・排水	○
Q16A9	産業廃棄物	○

Q17　現在、水素の用途として最も多いと思うものを3つお選びください。

Q17A1	石油精製所	○
Q17A2	水素自動車・水素バス	○
Q17A3	製鋼	○
Q17A4	家庭用燃料電池(エネファーム)	○
Q17A5	メタノール生産	○
Q17A6	アンモニア生産 (肥料)	○
Q17A7	暖房	○
Q17A8	エネルギー貯蔵	○

Q18　水素社会が実現することについて伺います。下記の事柄についてどう思いますか？

		とても問題である	問題である	どちらでもない	問題でない	まったく問題でない
Q18A1	水素自動車の普及	○	○	○	○	○
Q18A2	あなたの家の近くで家庭用燃料電池が使用されている	○	○	○	○	○
Q18A3	あなたの家の近くに水素貯蔵タンクが新しく建てられる	○	○	○	○	○
Q18A4	あなたの家の近くに水素パイプラインが埋設される	○	○	○	○	○
Q18A5*	あなたの家の近くのガソリンスタンドが水素を販売する	○	○	○	○	○
Q18A6*	あなたの家の近くに水素ステーションが新しく建てられる	○	○	○	○	○
Q18A7*	あなたの地域のバス会社が水素バスを導入する	○	○	○	○	○

Q19 水素のインフラについての意見です。あなたはどのように思いますか？それぞれについて、いずれか 1 つお選びください。

		そう思わない	あまり思わない	どちらともいえない	少し思う	そう思う
Q19A1	水素インフラ事故は広域に被害を及ぼす	○	○	○	○	○
Q19A2*	現時点では技術が信頼できない	○	○	○	○	○
Q19A3	水素インフラ関連の政策・規制の改善が必要	○	○	○	○	○
Q19A4	水素インフラは、安全性への懸念から周辺の不動産価格が下がる可能性	○	○	○	○	○
Q19A5	水素インフラはまだ不足している	○	○	○	○	○

※水素インフラは水素ステーション、水素パイプライン、水素貯蔵タンク

Q20 車を購入したり買い換えたりするときに、どんな車を選びますか？（いくつでも）

Q20A1	ガソリン自動車	○
Q20A2	電気自動車	○
Q20A3	ハイブリッド車	○
Q20A4	水素自動車	○
Q20A5	レンタカーを利用する	○
Q20A6	公共交通を利用する	○
Q20A7	車の購入も買い換えも検討しない	○

Q21 下記の車を購入したい理由をお選びください。（いくつでも）

		コスト	環境にやさしい	省エネルギー（高効率）機器	充電・給油所の有無	技術に理解がある
Q21A1	ガソリン自動車	○	○	○	○	○
Q22A2	電気自動車	○	○	○	○	○
Q21A2	ハイブリッド車	○	○	○	○	○
Q22A3	水素自動車	○	○	○	○	○

Q22 あなたにとって水素を利用するにあたり、下記事柄は必要だと思いますか？ それぞれについて、いずれか **1** つお選びください。

		そう思わない	あまり思わない	どちらともいえない	少し思う	そう思う
Q22A1	政策規制・安全基準の策定	○	○	○	○	○
Q22A2	水素関連技術のコストダウン	○	○	○	○	○
Q22A3	水素インフラの整備	○	○	○	○	○
Q22A4	水素技術利用に対する税制優遇措置の提供	○	○	○	○	○
Q22A5	水素技術に関する知識の普及	○	○	○	○	○

Q22b 水素を利用することに対して、他の理由があれば、記述してください。

Appendix D. Expert Survey Questionnaire

Hydrogen Economy Expert Survey

Introduction

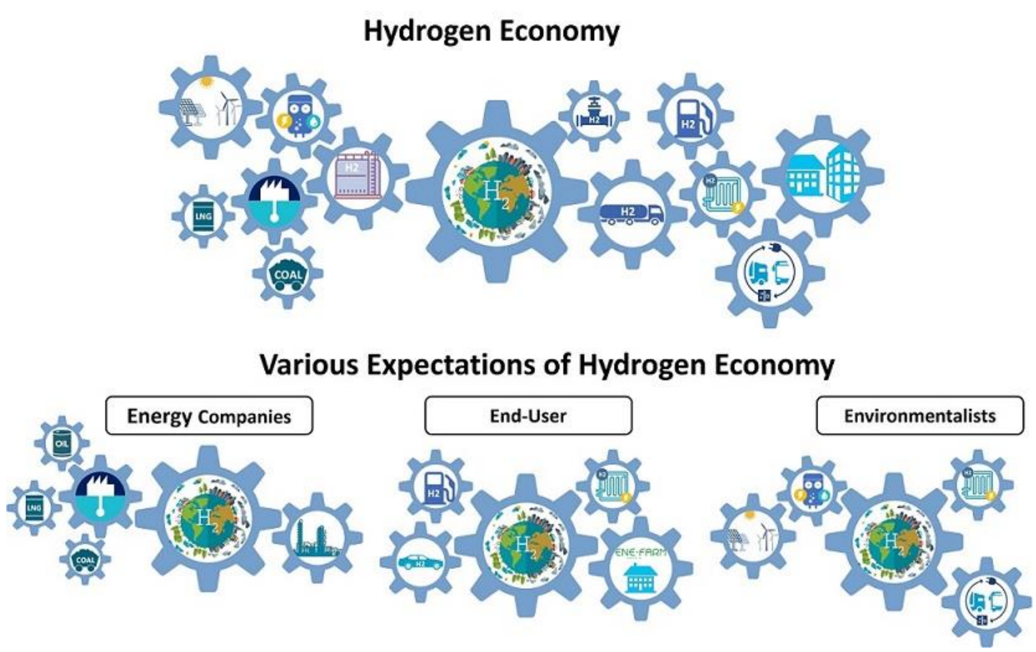
Thank you for taking the time to participate in our survey.

I am a doctoral candidate at Kyoto University's Graduate School of Energy Science, researching the potential for a future hydrogen economy.

The aim of this study is to evaluate both global and country-specific aspects of the transition to a hydrogen economy. The study has two objectives. Firstly, it seeks to gather expert opinions on motivations, drivers, and barriers to adopting hydrogen technology, as well as the current state of the industry, in order to determine whether these factors have evolved over time. Secondly, the study seeks to clarify the different, yet overlapping interpretations of the hydrogen economy among expert groups.

This survey will take approximately 10 minutes to complete. Your answers will be treated with complete confidentiality. The presentation of any results will be anonymized to protect the privacy of respondents.

If you have any questions about this survey, please contact me, Yap Jiazhen at yap.jiazhen.76z@st.kyoto-u.ac.jp



Section 1: Personal Information

1. What is your current professional affiliation?
(Please select the choice that best describe you)

- ○ Academicians (professors, researchers, scientists, educators)
- ○ Industry Professionals (engineers, energy consultants, technology developers, financial analysts, manufacturing supervisors, energy journalists)
- ○ Government or Policy-making (government officials, regulators, policy makers, international organization)

2. What is your current job position and the name of the organization or company that you work for?
(Ex: Professor - Kyoto University, Energy Analyst - IEA, Engineer - TEPCO)

3. How many years of experience do you have in the Energy field?
(Please provide your answer in numerical format)

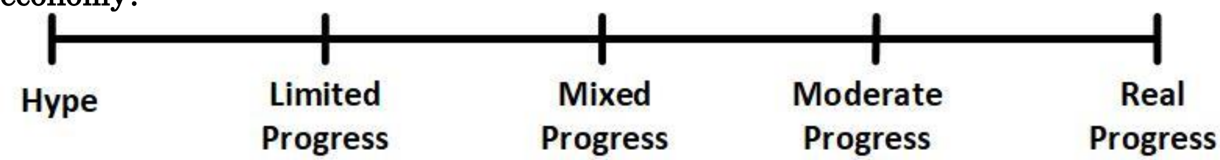
4. How many years of experience do you have in the Hydrogen field?
(Please provide your answer in numerical format)

5. If you would like to participate in our follow-up interview and discuss in detail, please provide your name and email address.

Section 2: What is a Hydrogen Economy

6. Which country do you primarily base your knowledge of the hydrogen economy on?
(Please note that your subsequent answers in this survey will be expected to reflect the context of this country)

7. Based on your experience, how would you rate the progress of the hydrogen economy?



Hype: The hydrogen economy has not lived up to its expectations and is more hype than reality. Despite the attention it has received, the progress has been minimal, and it is unlikely to become a major player in the global energy landscape.

Limited Progress: The hydrogen economy, including production, storage, distribution, and utilization, has seen minor improvements, but overall growth remains slow and is largely underdeveloped.

Mixed Progress: The development of the hydrogen economy has been mixed, with some areas showing progress, while others remain stagnant or face challenges. it is currently difficult to determine the likelihood of its eventual implementation as a dominant energy carrier.

Moderate Progress: There has been meaningful progress in various aspects of the hydrogen economy, but some challenges still need to be addressed for it to reach its full potential.

Real Progress: Significant advancements have been made in hydrogen production, storage, distribution, and utilization technologies. The hydrogen economy is rapidly developing and becoming a viable alternative to fossil fuels.

Hype	Limited Progress	Mixed Progress	Moderate Progress	Real Progress
○	○	○	○	○

8. What role do you believe hydrogen will play in the future by the year 2050?

- ○ **Major role**, as a key alternative to traditional fossil fuels
- ○ **Moderate role**, as one of several clean energy sources
- ○ **Minor role**, as a niche technology with limited applicability
- ○ **No role**, as other clean energy sources are more viable

9. If hydrogen were to develop into an internationally traded commodity, which position would best characterize the status of your country?

○ **No significant hydrogen use or production:** Your country does not use or produce hydrogen in significant quantities.

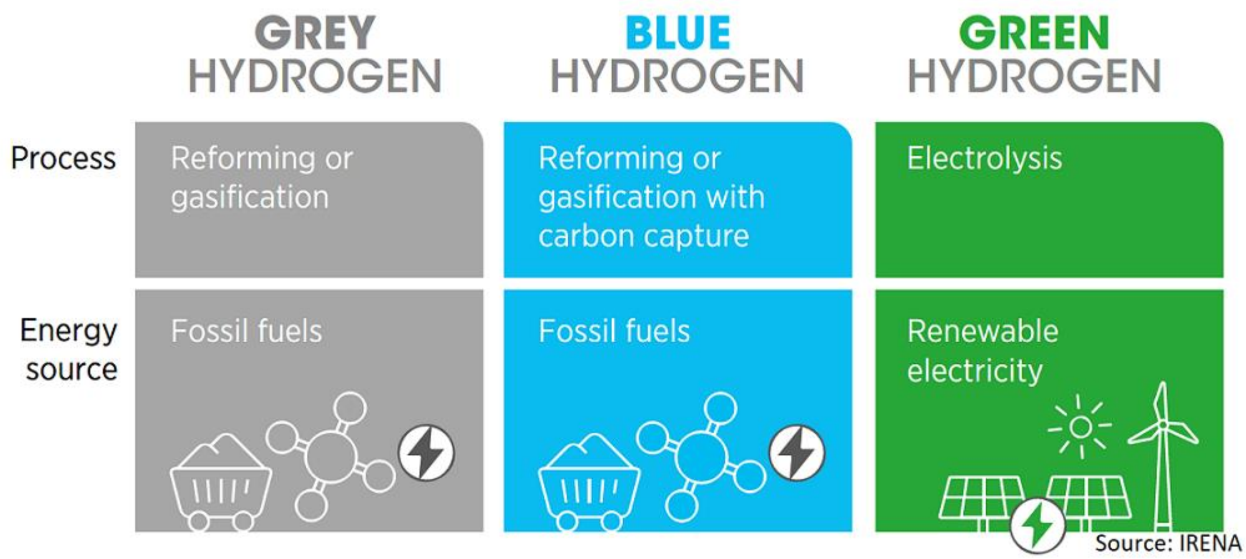
○ **Transit hub:** Your country serves as a transportation hub for hydrogen, facilitating its transfer between other countries.

○ **Localized market:** Your country produces and uses hydrogen primarily for domestic purposes, with little or no involvement in international trade.

○ **Net importer:** Your country is a significant importer of hydrogen and relies heavily on imports to meet domestic demand for hydrogen.

○ **Net exporter:** Your country is a significant hydrogen exporter, dedicating its entire production capacity to serving foreign markets due to the absence of domestic consumption.

10. Which of the following hydrogen production methods do you think should be used in the short term, middle term, and long term?



	Grey Hydrogen	Blue Hydrogen	Green Hydrogen
Short term (2030)	☐	☐	☐
Middle Term (2050)	☐	☐	☐
Long Term (Beyond 2050)	☐	☐	☐

11. In which sector of the economy does your country see hydrogen playing a key role?
(Please provide answers for all of the following items)

	No Usage	Low Usage	Medium Usage	High Usage
Transport (Road – Passenger)	○	○	○	○
Transport (Road – Freight)	○	○	○	○
Transport (Maritime)	○	○	○	○
Transport (Aviation)	○	○	○	○
Power Generation	○	○	○	○
Energy Storage	○	○	○	○
Industry (Chemical)	○	○	○	○
Industry (Steel Making)	○	○	○	○
Industry (Oil Refining)	○	○	○	○
Commodity for Export	○	○	○	○

12. This is an open-ended question inviting you to share your insights and experiences regarding the hydrogen economy.
(Please feel free to answer in as much detail as you like, using the language of your choice, based on some of the examples)

Understanding: Could you provide your personal definition or understanding of what a 'hydrogen economy' means? Are there any particular aspects or features of a hydrogen economy that stand out to you?"

Reasoning Behind Choices: Could you elaborate on the reasoning behind your choices? For instance, why did you select the particular role for hydrogen in the future, or the preferred method for hydrogen production over time?

Progress Evaluation: Based on your knowledge or experience, how would you suggest tracking the progress of the hydrogen economy? What key indicators or milestones should we look for?

Personal Experiences: Are there any specific experiences, projects, or case studies you've been involved with that relate to the hydrogen economy? Can you share these experiences and explain how they have shaped your perspective?

Expectations: What do you expect to see in the future of the hydrogen economy? Can you explain why you hold these expectations?

Section 2: Hydrogen Economy Drivers & Barriers

13. In your opinion, how important are the following drivers for your country to develop hydrogen policies and strategies?
(Please provide answers for all of the following items)

Social Drivers: Social drivers encompass the attitudes, preferences, and behaviors of the public towards hydrogen technologies. This includes public awareness, acceptance, and understanding of the positive health outcomes resulting from reduced air pollution, as well as the potential for increased energy access and demand for cleaner, more sustainable energy options.

Technological Drivers: Technological drivers relate to advancements in hydrogen-related technologies, including production, storage, distribution, and utilization. These advancements may include improvements in electrolysis, fuel cells, hydrogen storage systems, and related infrastructure.

Economic Drivers: Economic drivers refer to the financial considerations associated with hydrogen technologies. These drivers include factors such as the cost competitiveness of hydrogen compared to other energy sources, job creation potential, economic growth, and energy security.

Environmental Drivers: Environmental drivers encompass the environmental benefits and impacts associated with hydrogen technologies. They include factors such as reduced greenhouse gas emissions, air pollution mitigation, and overall environmental sustainability.

Political & Institutional Drivers: Political and institutional drivers encompass the policies, regulations, and governance frameworks put in place by governments and institutions to support hydrogen development. They include factors such as government incentives, supportive legislation, research funding, and international collaborations.

	No Importance	Low Importance	Medium Importance	High Importance
Social Drivers	○	○	○	○
Technological Drivers	○	○	○	○
Economic Drivers	○	○	○	○
Environmental Drivers	○	○	○	○
Political & Institutional Drivers	○	○	○	○

14. In your opinion, what are the current drivers for the implementation of a hydrogen economy in your selected country? Additionally, reflecting upon the drivers that were predominant when you first began your work in the hydrogen field, do you see an overlap between the past and present drivers, or have they changed over time?

(Please select either the past, present, none, or both)

Explanation on how to answer the question

	Past	Present	
Environmental concerns about carbon emissions	☑	☐	Past drivers that are no longer valid in the present
Enhancing energy security through diversification of energy resources	☑	☑	Relevant drivers from the past that continue to persist in the present
Generating employment and stimulating economic growth	☐	☐	Drivers that were absent both in the past and the present
Developing hydrogen as an export commodity	☐	☑	Emerging drivers that were not prominent in the past

	Past	Present
Environmental concerns about carbon emissions	☐	☐
Enhancing energy security through diversification of energy resources	☐	☐
Generating employment and stimulating economic growth	☐	☐
Developing hydrogen as an export commodity	☐	☐
Serving as an energy carrier in sectors difficult to decarbonize	☐	☐
Hydrogen production can make use of surplus generation capacity from nuclear and renewable energy sources	☐	☐
Reducing dependency on fossil fuels	☐	☐
Utilizing hydrogen as an energy storage solution	☐	☐
Global momentum towards a hydrogen economy	☐	☐

Other (please specify)

15. In your opinion, how important are the following barriers for your country to develop hydrogen policies and strategies?
(Please provide answers for all of the following items)

Social Barriers: Social barriers refer to the challenges related to public acceptance, awareness, and attitudes towards hydrogen technologies. These barriers can include skepticism or a lack of understanding about hydrogen, concerns about safety, and resistance to change.

Technological Barriers: Technological barriers encompass challenges associated with the development and deployment of hydrogen-related technologies. These barriers can include limitations in hydrogen production methods, inefficient storage and transportation infrastructure, and the need for further research and development.

Economic Barriers: Economic barriers involve the financial challenges and considerations associated with hydrogen technologies. These barriers can include high production costs, the lack of a well-established market for hydrogen, and the need for significant infrastructure investments.

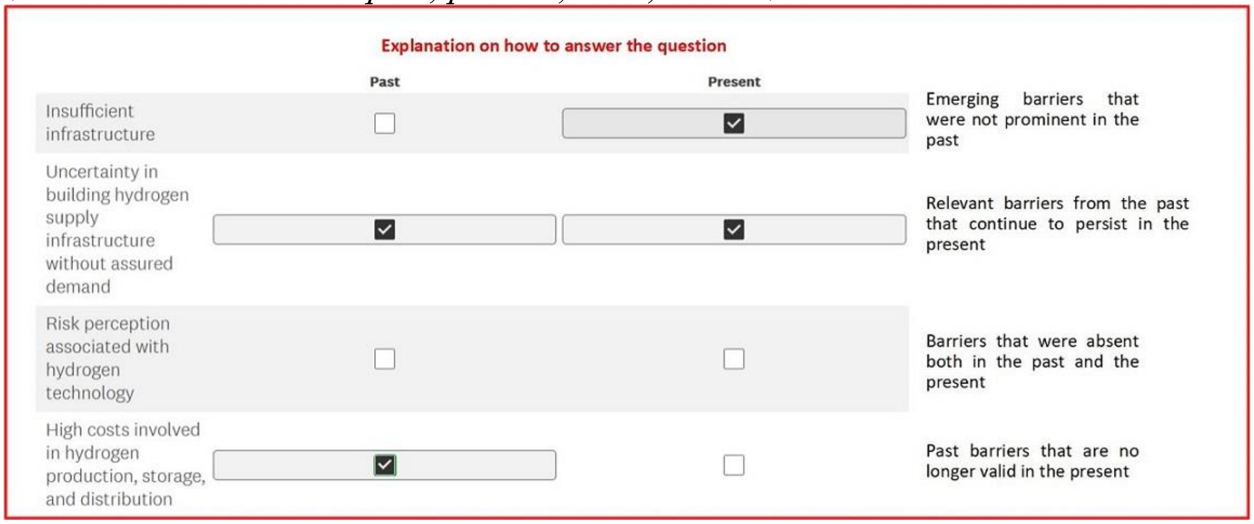
Environmental Barriers: Environmental barriers relate to challenges or concerns regarding the environmental impact of hydrogen technologies. These can include issues such as the carbon intensity of hydrogen production methods, unsustainable usage of water for hydrogen production, and the overall life cycle emissions.

Political & Institutional Barriers: Political and institutional barriers involve challenges arising from the policies, regulations, and governance frameworks that impact hydrogen development. These barriers can include the lack of clear and supportive policies, inadequate regulatory frameworks, and inconsistent government support.

	No Importance	Low Importance	Medium Importance	High Importance
Social Barriers	○	○	○	○
Technological Barriers	○	○	○	○
Economic Barriers	○	○	○	○
Environmental Barriers	○	○	○	○
Political & Institutional Barriers	○	○	○	○

16. In your opinion, what are the current barriers for the implementation of a hydrogen economy in your selected country? Additionally, reflecting upon the barriers that were predominant when you first began your work in the hydrogen field, do you see an overlap between the past and present barriers, or

have they changed over time?
(Please select either the past, present, none, or both)



Explanation on how to answer the question

	Past	Present	
Insufficient infrastructure	☐	☑	Emerging barriers that were not prominent in the past
Uncertainty in building hydrogen supply infrastructure without assured demand	☑	☑	Relevant barriers from the past that continue to persist in the present
Risk perception associated with hydrogen technology	☐	☐	Barriers that were absent both in the past and the present
High costs involved in hydrogen production, storage, and distribution	☑	☐	Past barriers that are no longer valid in the present

	Past	Present
Inadequate infrastructure for end-use applications	☐	☐
Uncertainty in building hydrogen supply infrastructure without assured demand	☐	☐
Risk perception associated with hydrogen technology	☐	☐
High costs involved in hydrogen production, storage, and distribution	☐	☐
Technical challenges in storage and transportation of hydrogen	☐	☐
Competition from clean energy	☐	☐
Uncertain market potential	☐	☐
Low technological maturity of hydrogen applications	☐	☐
Limited public acceptance due to lack of information about hydrogen	☐	☐
Absence of a comprehensive regulatory framework and standards for hydrogen	☐	☐
Resource constraints (water, land, etc)	☐	☐

Other (please specify)

17. This is our final question. Feel free to offer any closing remarks on the topic of the hydrogen economy or its drivers and barriers.
(Please feel free to answer in as much detail as you like, using the language of your choice)

List of Publications

Journal Papers

Yap J, McLellan B. A Historical Analysis of Hydrogen Economy Research, Development, and Expectations, 1972 to 2020. Environments 2023;10. https://doi.org/10.3390/environments10010011 *(Cover Story for Environments, Volume 10, Issue 1, 2023)*

Yap J, McLellan B. Evaluating the attitudes of Japanese society towards the hydrogen economy : A comparative study of recent and past community surveys. Int J Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.05.174

Yap J, McLellan B. Exploring Global and Country-Specific Transitions to a Hydrogen Economy: Insights from Expert Surveys. Int J Hydrogen Energy 2023 [*Under Submission*]

Conference Papers

J. Yap and B. C. Mclellan, "Assessing Public Acceptance on Hydrogen Economy in Japan: A Comparison of Past Survey In 2015," 23rd World Hydrogen Energy Conference 2022 (WHEC 2022), Jun 26-30, 2022, Istanbul, Turkey.

J. Yap and B. C. Mclellan, "The Historical Mapping of the Hydrogen Economy," *第37回エネルギーシステム・経済・環境コンファレンス*, pp. 210–215, 2021.

Other Publication

Chapman A, McLellan B, Mabon L, Yap J, Karmaker SC, Sen KK. The Just Transition in Japan: Awareness and desires for the future. Energy Res Soc Sci 2023;103:103228. https://doi.org/10.1016/j.erss.2023.103228.