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

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Abstract

The Japanese government has long supported efforts to achieve a hydrogen society, but it is yet to be seen if hydrogen can achieve large-scale deployment. 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 a previous survey in 2015 to understanding of changing attitudes over time. The results show a gap in public understanding of hydrogen, with actual knowledge lower than self-reported. The Japanese community is divided on green vs. grey hydrogen production, with cost and environment being key factors. Public perception is neutral with positive inclination but understanding of production and utilization differs from reality. Acceptance for hydrogen applications varies, with transportation receiving the most support. This study serves as basic information in establishing an operational and inclusive hydrogen economy that aligns with the collective desires and needs of all stakeholders.

Keywords: Hydrogen Economy, Survey, Public Acceptance, Public Perception, Japan

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 [1]. The hydrogen economy transition is a dynamic system that consists of economic, technological, and social structures that are constantly evolving. This dynamic system 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 as an energy solution inadvertently allows people to interpret it based on their agendas, resulting in competing interpretations of what a future hydrogen economy may look like [2]. This has created a gap between the public and scientific community understanding of the status of hydrogen economy and raised false expectations in the past [3]. It is widely accepted in socio-economics that the success of emerging technology depends to a great extent on public acceptance [4,5]. Emerging technologies such as hydrogen technology have received increased general coverage through the media [6], but public perception and acceptance are still relatively unknown [7].

1.1. Japan and Hydrogen Economy

Japan has a long history 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 [8]. The national program objective is to develop new energy technology - mainly solar energy, geothermal energy, coal energy, hydrogen energy, and supporting research [9]. 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. The WE-NET project is a long-term plan to create a global energy network by using hydrogen produced by renewable energy [10,11]. 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 [12]. In the subsequent year, the ratification of the Paris Agreement further bolsters Japan’s plan of a hydrogen-based society to address critical climate change issues by limiting global warming to well below 2°C [13].

As the energy sector continues to evolve, the roadmap along with technology milestones have been revised in 2016 [14] and 2019 [15] to establish achievable targets considering international cooperation, technology advancement, and societal needs [16]. 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 [17]. 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) [18] projected five million fuel cell vehicles (FCV) by 2020, while the Japanese government, in a more conservative projection, forecast forty thousand FCV by 2020 in their 2017 report [19]. However, the International Energy Agency (IEA) only reported over six thousand six hundred FCV on the road in Japan in 2021 [20].

1.2. Aim

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 [21,22]. Hydrogen is an energy carrier, which needs to be produced, stored, transported, and distributed in an energy network [3]. 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 therefore 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 a previous survey in 2015 [7]. 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 (forthcoming work by the authors) with an expert panel survey that aims to quantify 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.

The paper is structured as follows. Section 2 presents and summarizes the available literature on hydrogen survey-based studies while section 3 introduces the methodological approaches in the evaluation of public perception and acceptance towards a hydrogen economy. Section 4 presents the survey results and their implications under key themes. The paper concludes by summarizing the findings and a discussion of possible directions for future research using the knowledge gained.

2. Literature Review

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 [23,24]. However, the social aspects, particularly the study of public perception or acceptance of hydrogen, has been significantly less frequent [25].

Country-specific studies such as for Germany [4,26,27], USA [28,29], England [30,31], and Spain [5] have investigated the acceptance and implementation of hydrogen technology. In a more localized study, Heinz & Erdmann [32] conducted a questionnaire survey in eight different European cities to compare public attitudes towards hydrogen technologies. In a similar study, Ingaldi and Klimecka-Tatar [33] 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 [26].

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 [31,34,35], 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 [36] and Ecological City Transport System (ECTOS), a demonstration project in Reykjavik, Iceland, using fuel cell buses as well [37,38]. 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 [21].

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 [39] and 2009 [40],

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. [7] 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. [41] 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 [21]. 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 [42].

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 [34]. However, the London study encompassed fuel cell vehicles [30] and hydrogen refueling stations [31]. Thesen and Langhelle [43] further extended the ACCEPTH2 study by employing the same set of questionnaires used in the London study [30], 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 [28]. 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 [29]. The current study follows a similar approach, in that it seeks to compare the results of previous surveys in Japan with the present.

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 [44], 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 comprehensive 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**. [21,22,45,46]. In this paper, 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. Table 1 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 1: Summary of Literature Review – Studies analysing public perception or acceptance of hydrogen economy

Ref	Survey Year	Location	Respondent	Method	Technology			Socio-Economic			
					Production	Storage	End use	Knowledge	Value	Perception	Acceptance
[37]	2001	Iceland	1154	Interview			•	•		•	•
[30]	2003	London	414	Interview			•	•	•	•	•
[47]	2003	Netherlands	612	Questionnaire			•	•		•	•
[31]	2003	London	346	Questionnaire		•		•		•	•
[34]	2003-2004	4 cities ^c	1358	Interview			•	•	•	•	•
[35]	2004	Sweden	541	Questionnaire			•	•		•	•
[38]	2004	Iceland	200	Questionnaire			•	•		•	•
[28]	2004	USA	2224	Interview	•	•	•	•	•	•	•
[43]	2006	Norway	1000	Interview			•	•	•	•	•
[32]	2006	Europe	3353	Interview			•	•		•	•
[29]	2008-2009	USA	2825	Interview	•	•	•	•	•	•	•
[39]	2008 ^a	Japan	1188	Questionnaire		•	•	•	•	•	•
[40]	2009 ^a	Tokyo	800	Questionnaire		•	•	•	•	•	•
[48]	2009	Norway	1000	Interview		•	•	•	•		•
[4]	2010	Germany	1011	Interview			•	•	•	•	•
[49]	2010	Netherlands	1214	Questionnaire		•		•			•
[26]	2013	Germany	1000	Interview		•	•				•
[41]	2014	Japan	2069	Questionnaire		•		•	•	•	•
[5]	2015	Spain	1005	Questionnaire		•	•	•		•	•
[7]	2015 ^b	Japan	3133	Questionnaire		•	•	•	•	•	•
[27]	2016	Germany	141	Questionnaire		•		•		•	•
[50]	2018	Turkey	10	Interview				•			

[33]	2019 - 2020	Europe	766	Questionnaire			•	•	•		
-	2022	Japan	2880	Questionnaire	•	•	•	•	•	•	•

^a Indicates studies used for comparison

^b Indicates current study

^c The 4 cities are London, Munich, Luxembourg, and Perth

3. 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 [25], a theoretical model was adapted to guide the formulation of the survey questions. The following model in Figure 1 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 [2]. 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 [51]. 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 [52]. 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 [53].

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 [3]. 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[22].

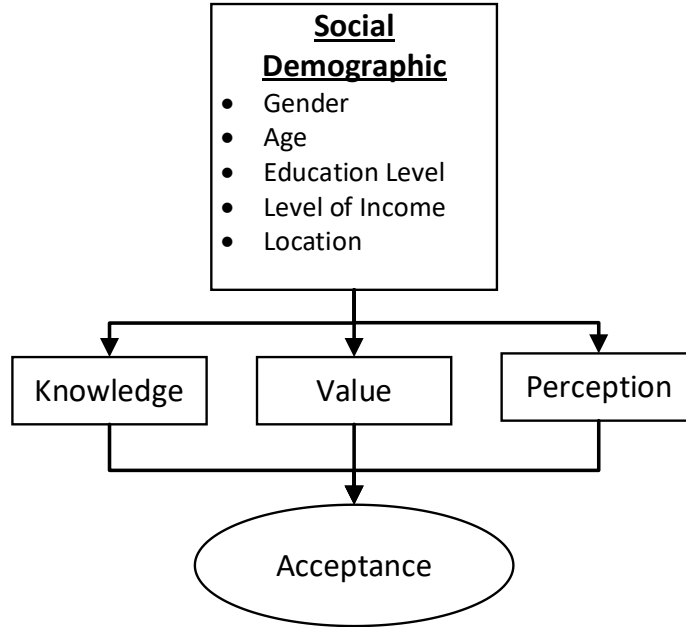


Figure 1: Theoretical Model of Public Acceptance of Hydrogen

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 [7], 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. A total of 2880 respondents were proportionally selected from the eight administrative regions of Japan based on Japan's 2020 population census [54]. 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 [55]. 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 2 summarizes the social demographics of respondents.

Table 2: 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. 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 3.

Table 3: 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

4.1. 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".

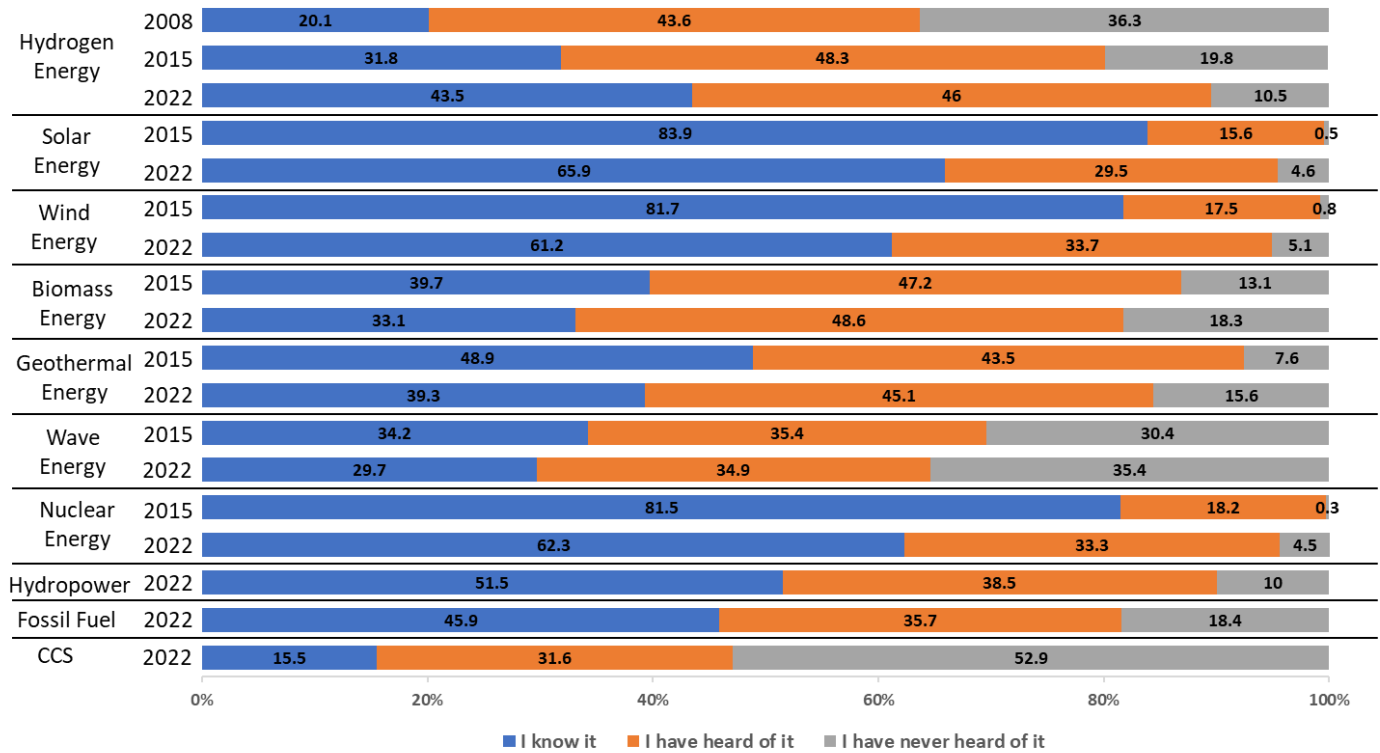


Figure 2: Self-reported knowledge of various energy resources & technologies

Figure 2 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.

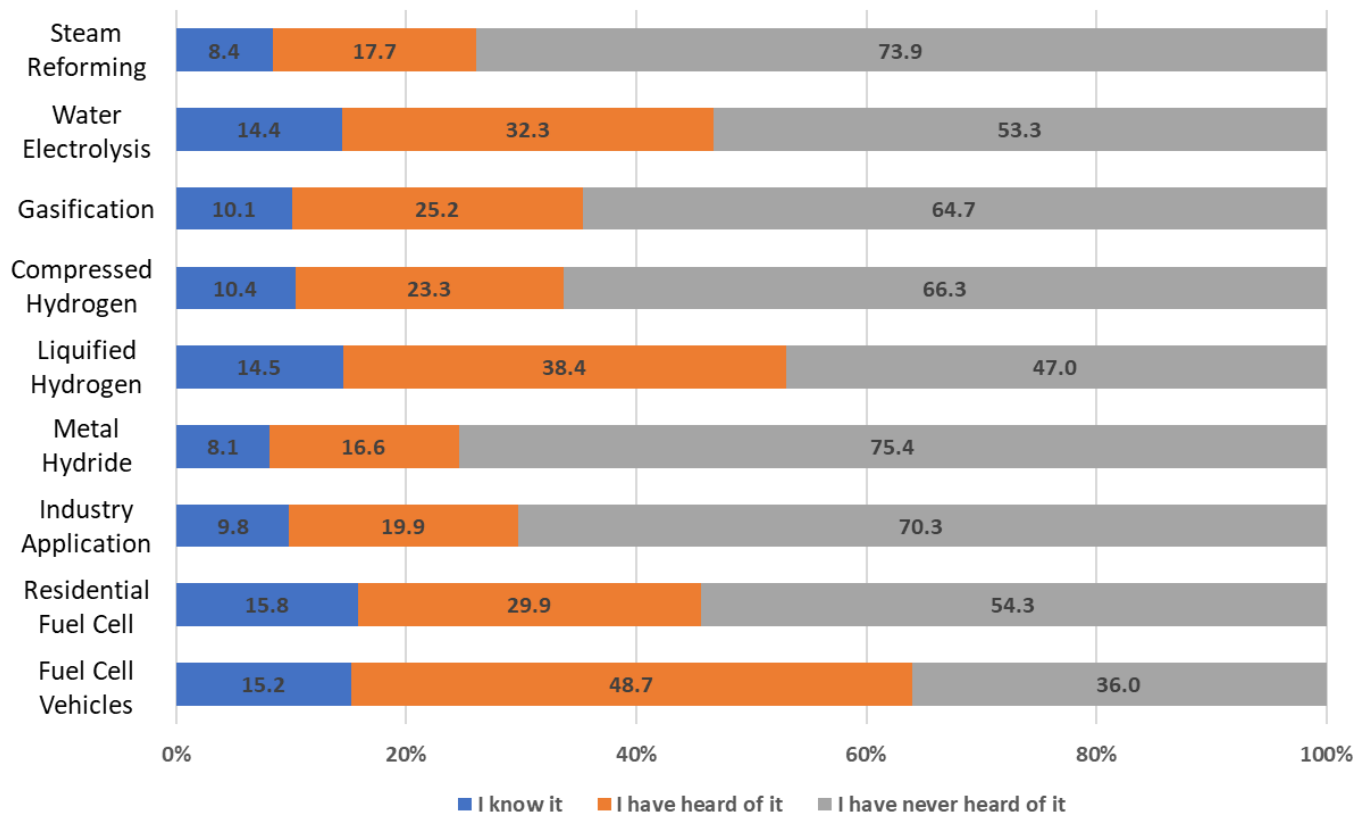


Figure 3: Self-reported knowledge of various hydrogen-based technologies

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 3. 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.

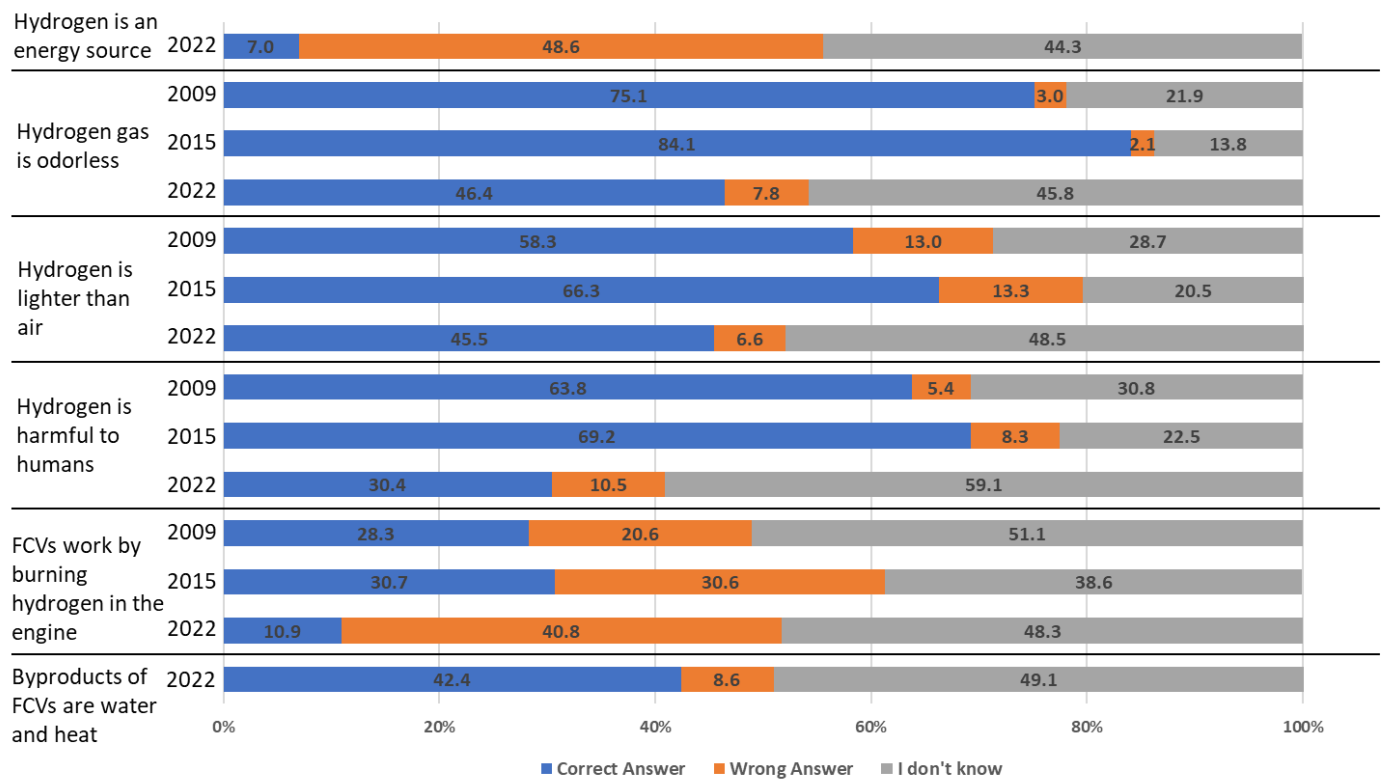


Figure 4: Objective knowledge on the properties of hydrogen and fuel cell vehicles

Six questions about the properties of hydrogen and fuel cell vehicles were specifically developed to gauge public knowledge on hydrogen, as shown in Figure 4. 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.

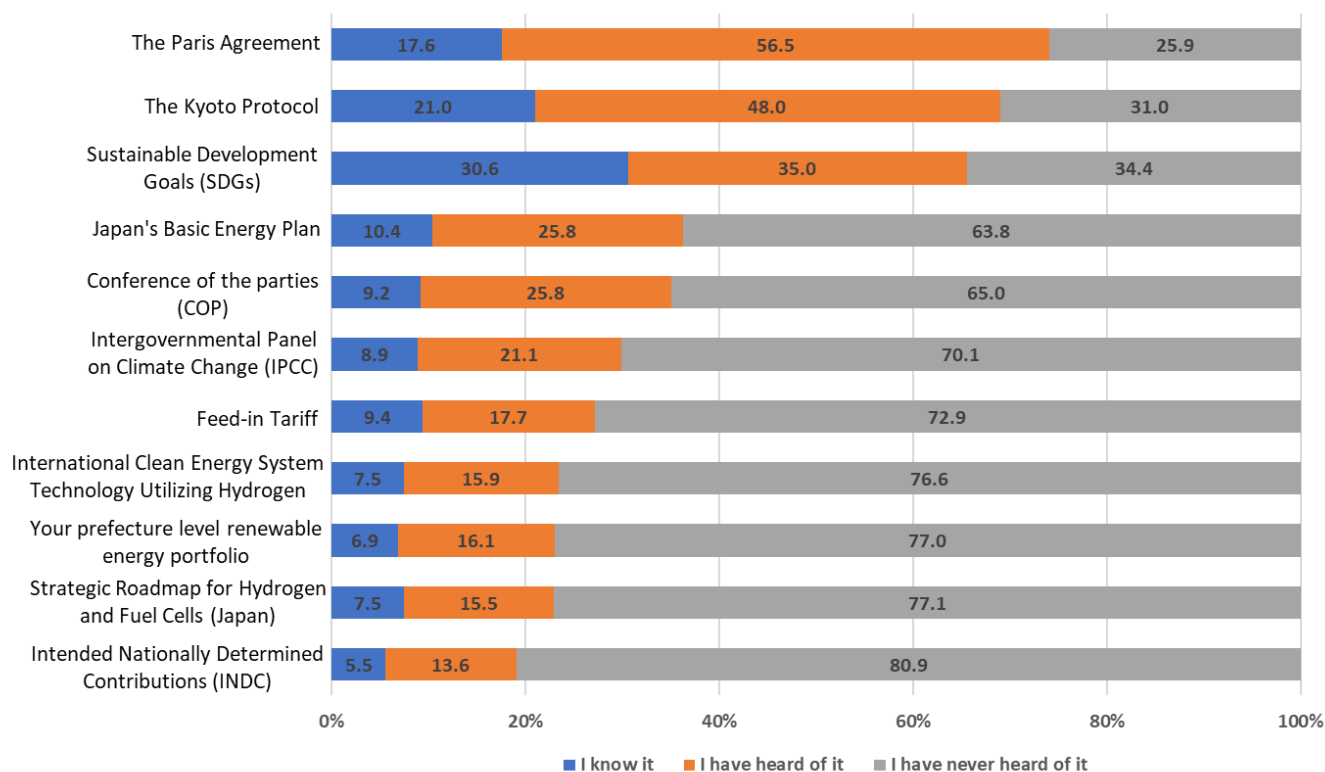


Figure 5: Self-reported knowledge of various energy-related policy

Figure 5 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 [56], policies pertaining to hydrogen are relatively unknown in the Japanese society.

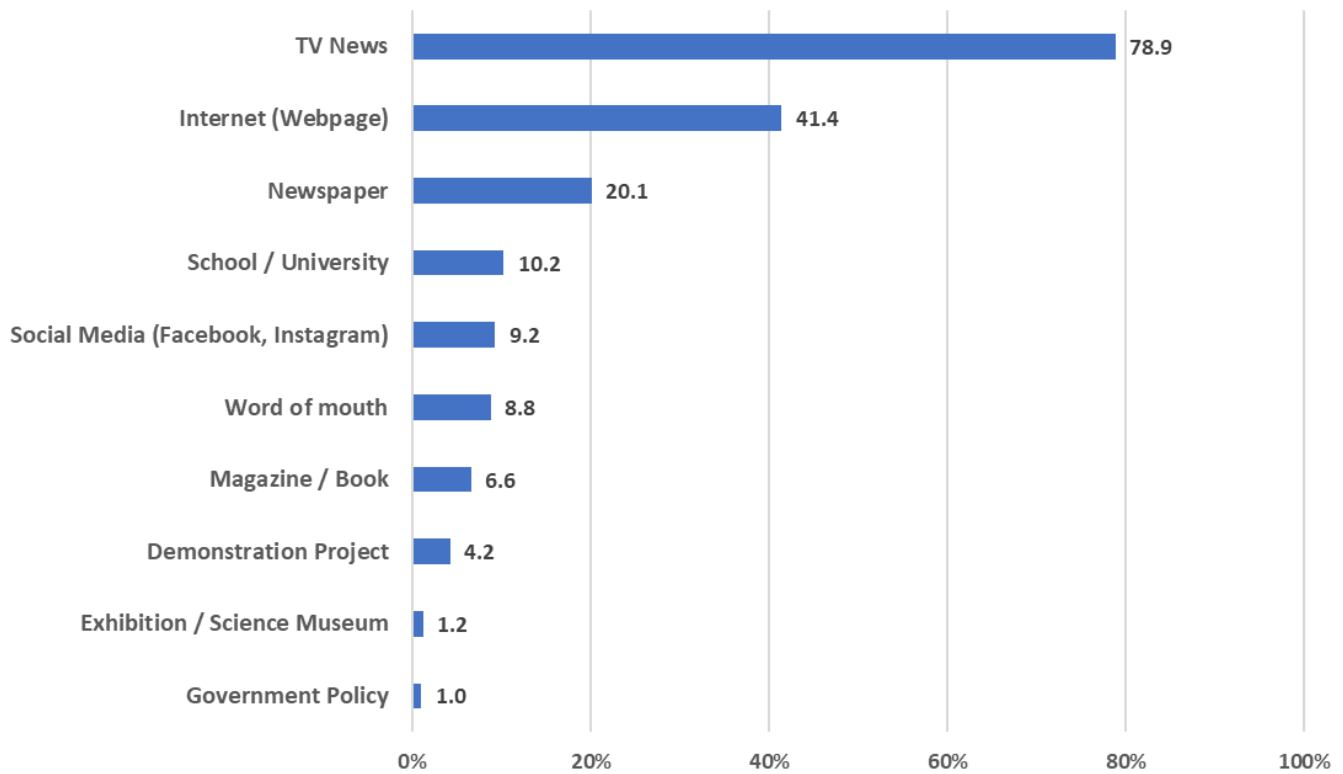


Figure 6: Sources of energy-related information for the respondents

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 6, 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 [57], the media can influence public perception of hydrogen in a non-neutral way, as well as how these perceptions are evaluated [26,58]. For example, the majority of media reports positively on the environmental benefits of hydrogen, often ignoring the actual situation surrounding hydrogen production [6]. This may result in people having a perception that differs from the actual situation (see Figure 10). 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 [7,22]. The rare exceptions are located in a few specific locations where the demonstration project or campaigns increased knowledge and generated public interest [21]. 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 [21]. 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 [44]. 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 [59]. 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 [44,60]. In summary, energy consumption is a common yet mostly unnoticed event for the average user, with the exception of supply disruptions or price increases.

4.2. 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 [53]. 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.

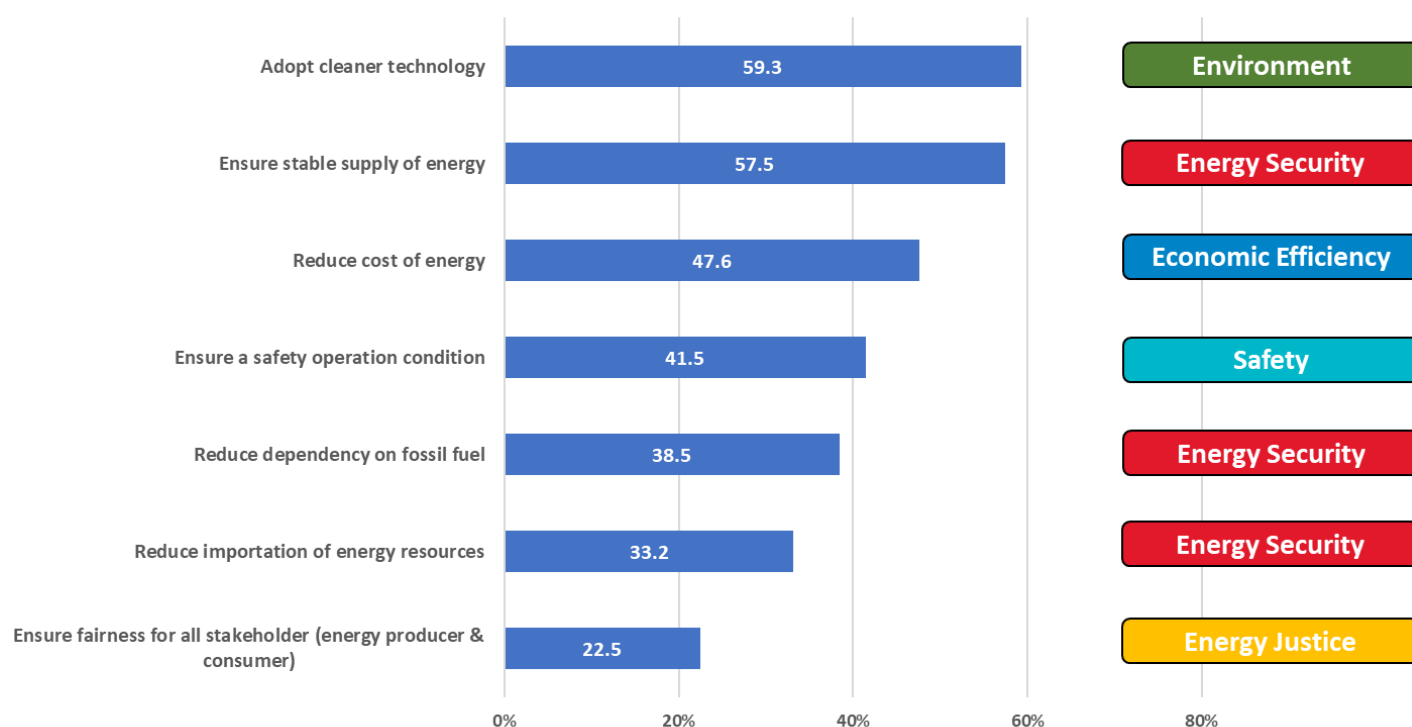


Figure 7: Personal priority in solving energy concerns

Figure 7 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%.

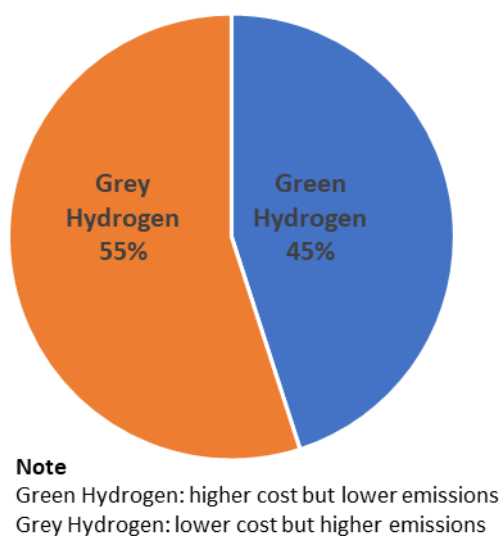


Figure 8: Preference of hydrogen production

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 [3]. 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 [3]. 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 [3]. 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 8. An interesting observation is that among

those who prioritized 'adopting cleaner technology' as a government energy concern (n=1401) (see Figure 7), 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 equal 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 [53]. 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. 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.

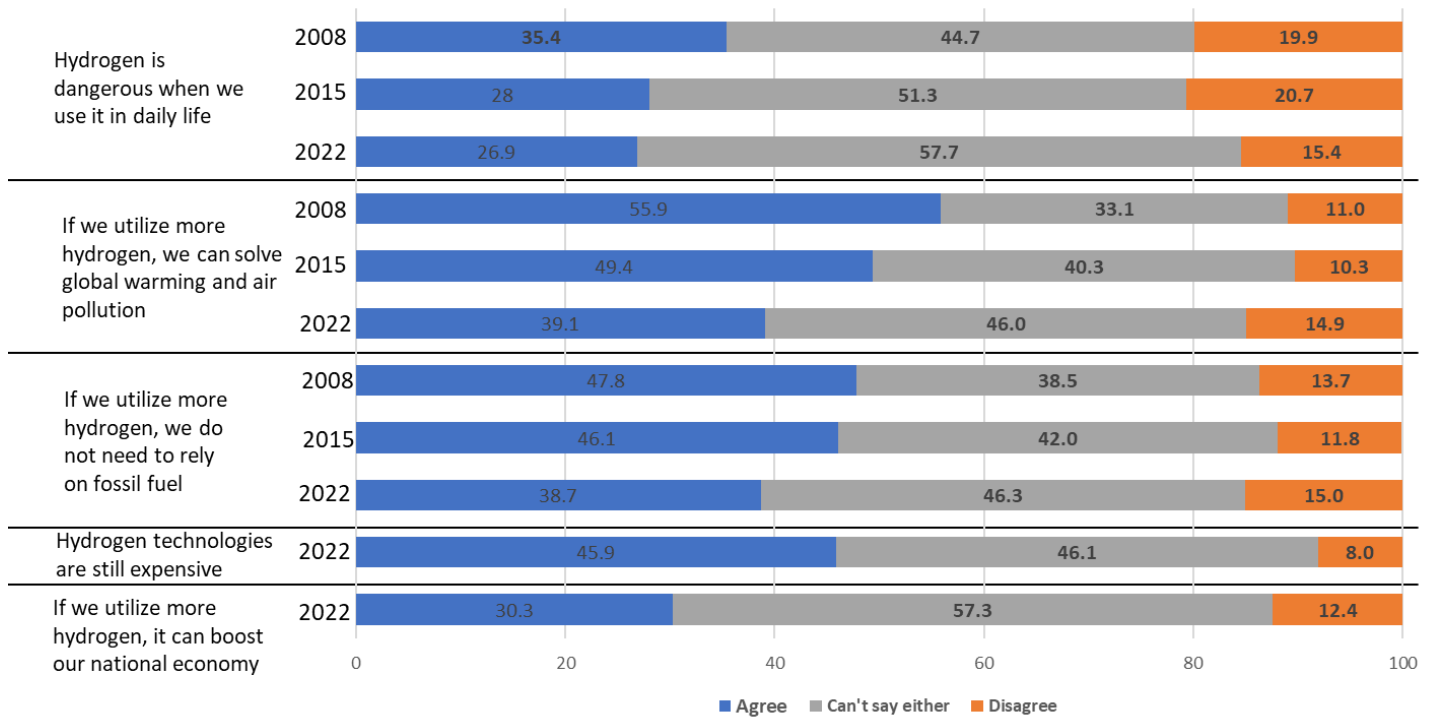


Figure 9: Public perception towards future hydrogen-based economy

In Figure 9, respondents were asked their opinions on five future hydrogen-based economy statements. Three statements were adapted from a previous study by Itaoka et al. [7], 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 has 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 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 [61]. 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.

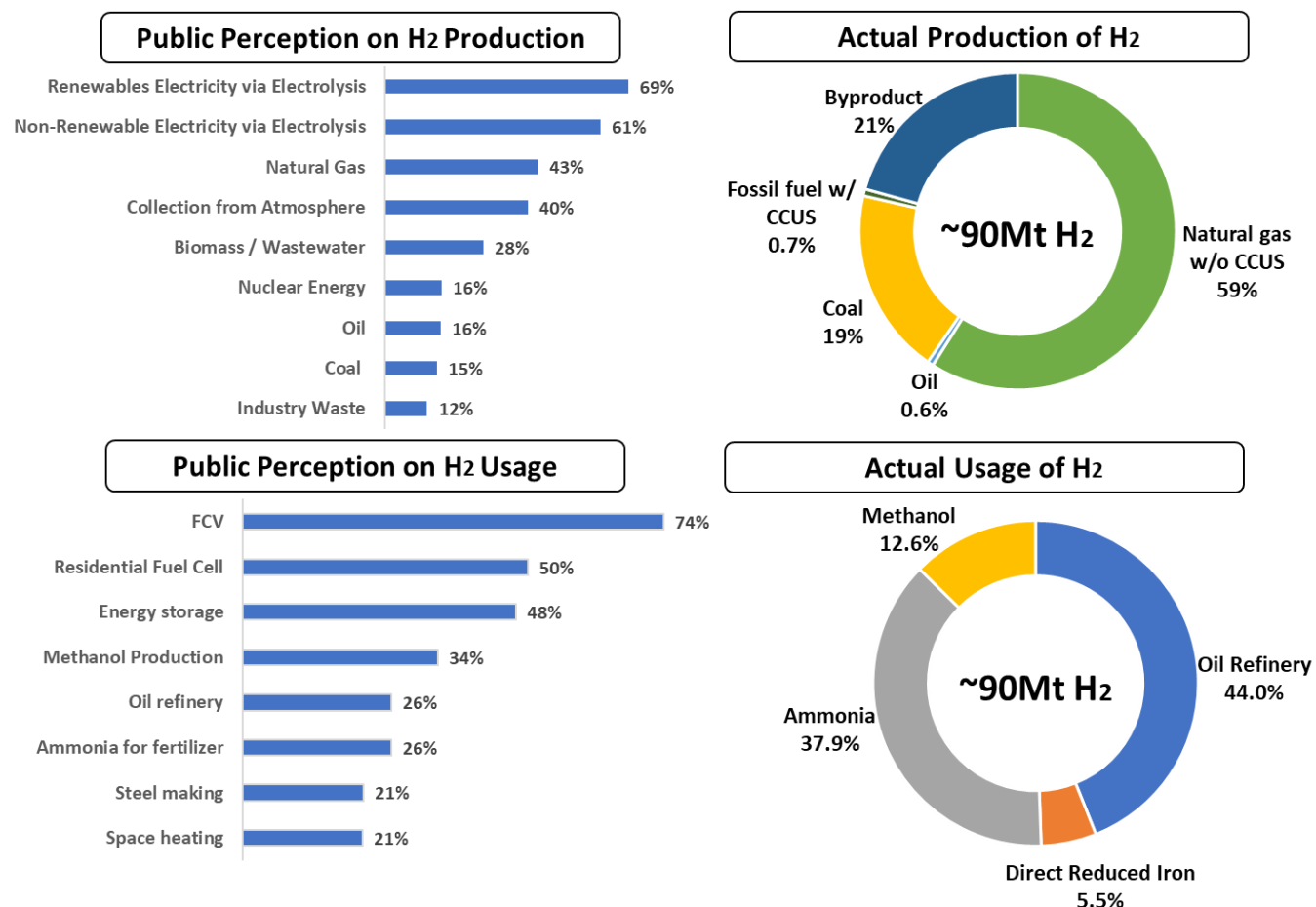


Figure 10: Comparison of public perceptions and reality of hydrogen production and usage

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" [62]. The survey reveals that they were mostly neutral and centered on topics such as "hydrogen water [63]", water (H₂O) 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 [62].

In Figure 10, 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 [64]. Many individuals believe that, in addition to natural gas (43%), electrolysis using either renewable (69%) or non-renewable electricity (61%) produces hydrogen. The results are not aligned with the actual production of hydrogen, which consists primarily of natural gas (59%), industrial byproducts (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 cell (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 with a positive inclination towards hydrogen, 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 [21]. 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 [65].

Public perceptions are formed by the combination of individual experiences, internal values, and external viewpoints [26]. 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 [27,66]. As a result, the viewpoints shaped by mass media may contribute to forming public perceptions in a biased, non-neutral way [67]. 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 [44].

4.4. 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 [27]. 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.

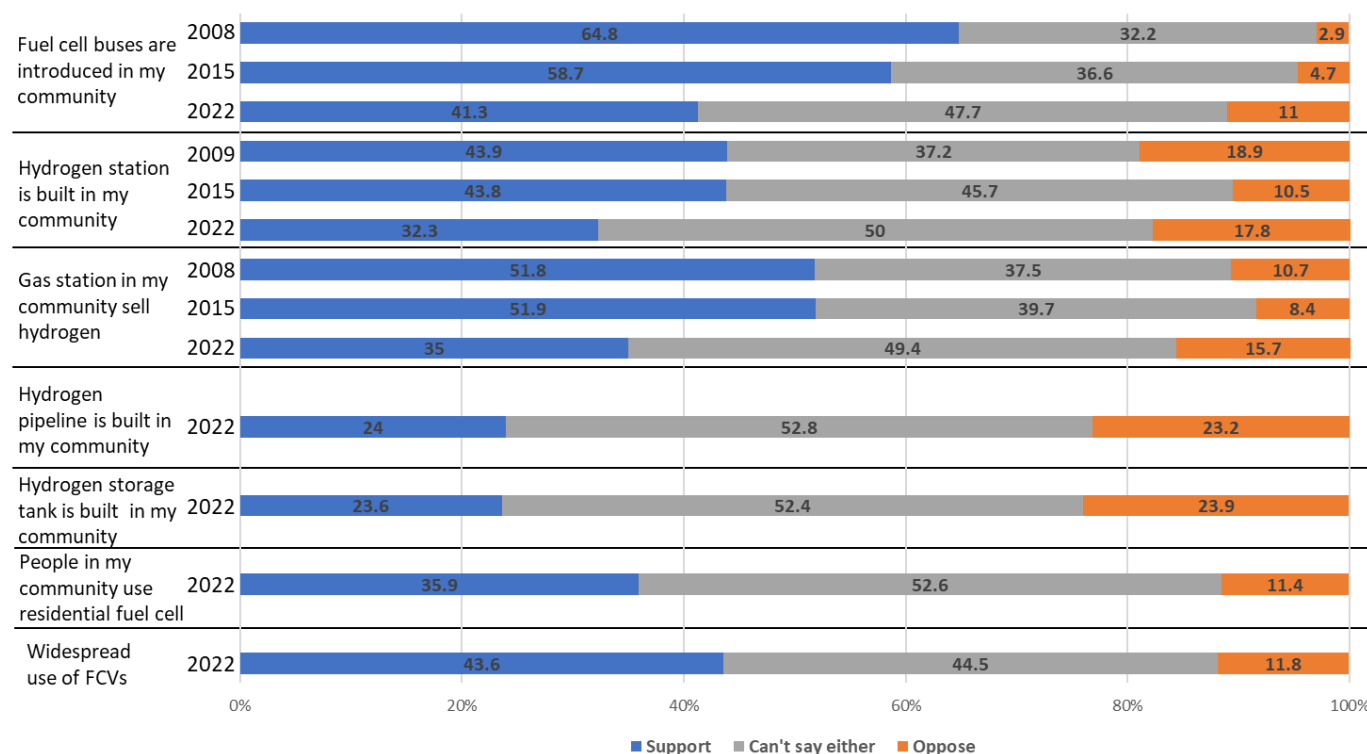


Figure 11: Public acceptance towards hydrogen-based economy

The acceptability of a future hydrogen-based economy was assessed by surveying respondents on their perspectives regarding hypothetical scenarios, as depicted in Figure 11. 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 9). 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 12. 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.

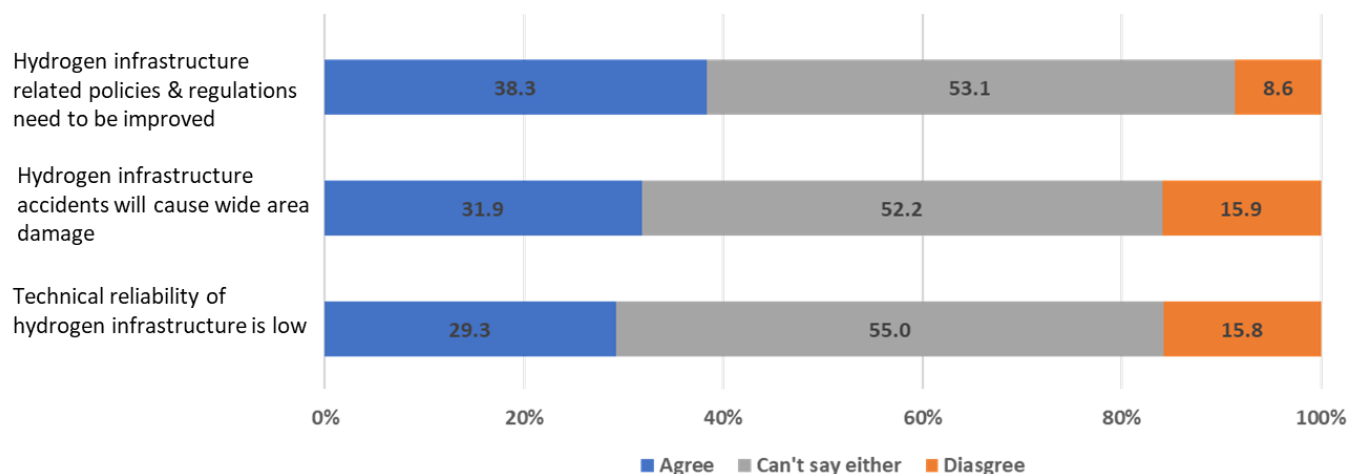


Figure 12: Risk perception of hydrogen infrastructure

Figure 12 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 [68]. 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 [69]. 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 [70]. 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. 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 [3]. 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.

5. Conclusion and Policy Recommendations

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 [44], 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 Japanese community is 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, leading to inquiries about 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 [12]. However, fuel cell vehicles face stiff competition from battery electric vehicles in the passenger sector due to the rapidly declining cost of batteries [71]. Opportunities may exist in the long-haul trucking sector, which faces significant challenges in decarbonisation 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 [72]. 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 [71].

Another important point concerns the production of hydrogen. Currently, hydrogen is predominately produced by non-renewable sources with high carbon emissions [64]. 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 [64]. 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 [73].

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.

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 [7] and refueling stations [41] in the Japanese community, the public acceptance of the hydrogen economy from a system perspective requires additional evaluation.

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.

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7. Declaration of competing interest

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

8. References

- [1] Moliner R, Lázaro MJ, Suelves I. Analysis of the strategies for bridging the gap towards the Hydrogen Economy. *Int J Hydrogen Energy* 2016;41:19500–8. <https://doi.org/10.1016/j.ijhydene.2016.06.202>.
- [2] 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>.
- [3] IEA. *The Future of Hydrogen*. Paris: 2019.
- [4] Zimmer R, Welke J. Let's go green with hydrogen! the general public's perspective. *Int J Hydrogen Energy* 2012;37:17502–8. <https://doi.org/10.1016/j.ijhydene.2012.02.126>.
- [5] Iribarren D, Martín-Gamboa M, Manzano J, Dufour J. Assessing the social acceptance of hydrogen for transportation in Spain: An unintentional focus on target population for a potential hydrogen economy. *Int J Hydrogen Energy* 2016;41:5203–8. <https://doi.org/10.1016/j.ijhydene.2016.01.139>.
- [6] Hultman M, Nordlund C. Energizing technology: Expectations of fuel cells and the hydrogen economy, 1990–2005. *Hist Technol* 2013;29:33–53. <https://doi.org/10.1080/07341512.2013.778145>.
- [7] Itaoka K, Saito A, Sasaki K. Public perception on hydrogen infrastructure in Japan: Influence of rollout of commercial fuel cell vehicles. *Int J Hydrogen Energy* 2017;42:7290–6. <https://doi.org/10.1016/j.ijhydene.2016.10.123>.
- [8] MITI Japan. JAPAN 'S SUNSHINE PROJECT SOLAR ENERGY R & D PROGRAM. 1981.
- [9] Takahashi K. Sunshine project in Japan - solar photovoltaic program. *Sol Cells* 1989;26:87–96. [https://doi.org/10.1016/0379-6787\(89\)90069-0](https://doi.org/10.1016/0379-6787(89)90069-0).
- [10] WE-NET Home Page n.d. http://www.enea.or.jp/WE-NET/contents_e.html (accessed December 30, 2021).
- [11] Mitsugi C, Harumi A, Kenzo F. WE-NET: Japanese hydrogen program. *Int J Hydrogen Energy* 1998;23:159–65. [https://doi.org/10.1016/S0360-3199\(97\)00042-6](https://doi.org/10.1016/S0360-3199(97)00042-6).
- [12] METI has compiled a Strategic Road Map for Hydrogen and Fuel Cells/ Ministry of Economy, Trade and Industry (METI) n.d. https://www.meti.go.jp/english/press/2014/0624_04.html (accessed December 31, 2021).
- [13] Schleussner CF, Rogelj J, Schaeffer M, Lissner T, Licker R, Fischer EM, et al. Science and policy characteristics of the Paris Agreement temperature goal. *Nat Clim Chang* 2016;6:827–35. <https://doi.org/10.1038/nclimate3096>.
- [14] Compilation of the Revised Version of the Strategic Roadmap for Hydrogen and Fuel Cells (METI) n.d. https://www.meti.go.jp/english/press/2016/0322_05.html (accessed December 31, 2021).
- [15] Formulation of a New Strategic Roadmap for Hydrogen and Fuel Cells n.d. https://www.meti.go.jp/english/press/2019/0312_002.html (accessed December 31, 2021).
- [16] Japan Hosts First Hydrogen Energy Ministerial Meeting n.d. https://www.meti.go.jp/english/press/2018/1023_007.html (accessed December 31, 2021).
- [17] Nagashima M. Japan's Hydrogen Society Ambition: 2020 Status and Perspectives 2020.
- [18] IEA. *Hydrogen and Fuel Cells Review of National R&D Programs*. 2004.
- [19] Government of Japan. *Basic Hydrogen Strategy*. 2017.
- [20] IEA. *Global EV Outlook 2022*. Paris: 2022.
- [21] Ricci M, Bellaby P, Flynn R. What do we know about public perceptions and acceptance of hydrogen? A critical review and new case study evidence. *Int J Hydrogen Energy* 2008;33:5868–80. <https://doi.org/10.1016/j.ijhydene.2008.07.106>.
- [22] Scovell MD. Explaining hydrogen energy technology acceptance: A critical review. *Int J Hydrogen Energy* 2022;47:10441–59. <https://doi.org/10.1016/j.ijhydene.2022.01.099>.
- [23] Nejat Veziroğlu T. Quarter century of hydrogen movement 1974–2000. *Int J Hydrogen Energy* 2000;25:1143–1150.
- [24] Nicoletti G. The hydrogen option for energy: A review of technical, environmental and economic aspects. *Fuel Energy Abstr* 1996;37:182. [https://doi.org/10.1016/0140-6701\(96\)88528-6](https://doi.org/10.1016/0140-6701(96)88528-6).

- [25] Schulte I, Hart D, Van der Vorst R. Issues affecting the acceptance of hydrogen fuel. *Int J Hydrogen Energy* 2004;29:677–85. <https://doi.org/10.1016/j.ijhydene.2003.09.006>.
- [26] Schmidt A, Donsbach W. Acceptance factors of hydrogen and their use by relevant stakeholders and the media. *Int J Hydrogen Energy* 2016;41:4509–20. <https://doi.org/10.1016/j.ijhydene.2016.01.058>.
- [27] Zaunbrecher BS, Bexten T, Wirsum M, Zieffle M. What is Stored, Why, and How? Mental Models, Knowledge, and Public Acceptance of Hydrogen Storage. *Energy Procedia* 2016;99:108–19. <https://doi.org/10.1016/j.egypro.2016.10.102>.
- [28] Schmoyer RL, Chew A. Results of the 2004 knowledge and opinions surveys conducted for the U.S. department of energy hydrogen program 2009.
- [29] Schmoyer RL, Truett T, Cooper C, Chew A. Results of the 2008/2009 knowledge and opinions surveys conducted for the U.S. department of energy hydrogen program. Oak Ridge Natl Lab 2010:1–299.
- [30] O'Garra T, Mourato S, Pearson P. Analysing awareness and acceptability of hydrogen vehicles: A London case study. *Int J Hydrogen Energy* 2005;30:649–59. <https://doi.org/10.1016/j.ijhydene.2004.10.008>.
- [31] O'Garra T, Mourato S, Pearson P. Investigating attitudes to hydrogen refuelling facilities and the social cost to local residents. *Energy Policy* 2008;36:2074–85. <https://doi.org/10.1016/j.enpol.2008.02.026>.
- [32] Heinz B, Erdmann G. Dynamic effects on the acceptance of hydrogen technologies-an international comparison. *Int J Hydrogen Energy* 2008;33:3004–8. <https://doi.org/10.1016/j.ijhydene.2008.02.068>.
- [33] Ingaldi M, Klimecka-Tatar D. People's Attitude to Energy from Hydrogen—From the Point of View of Modern Energy Technologies and Social Responsibility. *Energies* 2020;13:6495. <https://doi.org/10.3390/en13246495>.
- [34] O'Garra T, Mourato S, Garrity L, Schmidt P, Beerenwinkel A, Altmann M, et al. Is the public willing to pay for hydrogen buses? A comparative study of preferences in four cities. *Energy Policy* 2007;35:3630–42. <https://doi.org/10.1016/j.enpol.2006.12.031>.
- [35] Haraldsson K, Folkesson A, Saxe M, Alvfors P. A first report on the attitude towards hydrogen fuel cell buses in Stockholm. *Int J Hydrogen Energy* 2006;31:317–25. <https://doi.org/10.1016/j.ijhydene.2005.11.008>.
- [36] Perth Fuel Cell Bus Trial Summary of Achievements. Perth, Australia: 2008.
- [37] Maack MH, Skulason JB. Implementing the hydrogen economy. *J Clean Prod* 2006;14:52–64. <https://doi.org/10.1016/j.jclepro.2005.05.027>.
- [38] Maack MH. Report on social aspects of ECTOS - Hydrogen bus trial in Reykjavik 2014.
- [39] Information M, Institute R. Suiso shakaijuyousei ni kansuru chousa [Hydrogen's social acceptance research] 2008.
- [40] Information M, Institute R. Nenryoudenchi, suisu ni kansuru shakaijuyouseichousa [PEFC, Hydrogen's social acceptance research] 2009.
- [41] Ono K, Tsunemi K. Identification of public acceptance factors with risk perception scales on hydrogen fueling stations in Japan. *Int J Hydrogen Energy* 2017;42:10697–707. <https://doi.org/10.1016/j.ijhydene.2017.03.021>.
- [42] Hydrogen Europe. Post Covid- 19 and the Hydrogen Sector. Brussels, Belgium: 2020.
- [43] Thesen G, Langhelle O. Awareness, acceptability and attitudes towards hydrogen vehicles and filling stations: A Greater Stavanger case study and comparisons with London. *Int J Hydrogen Energy* 2008;33:5859–67. <https://doi.org/10.1016/j.ijhydene.2008.07.006>.
- [44] Boudet HS. Public perceptions of and responses to new energy technologies. *Nat Energy* 2019;4:446–55. <https://doi.org/10.1038/s41560-019-0399-x>.
- [45] Emodi NV, Lovell H, Levitt C, Franklin E. A systematic literature review of societal acceptance and

- stakeholders' perception of hydrogen technologies. *Int J Hydrogen Energy* 2021;46:30669–97. <https://doi.org/10.1016/j.ijhydene.2021.06.212>.
- [46] Gordon JA, Balta-Ozkan N, Nabavi SA. Beyond the triangle of renewable energy acceptance: The five dimensions of domestic hydrogen acceptance. *Appl Energy* 2022;324:119715. <https://doi.org/10.1016/j.apenergy.2022.119715>.
- [47] Molin E. Causal analysis of hydrogen acceptance. *Transp Res Rec* 2005;115–21. <https://doi.org/10.3141/1941-14>.
- [48] Tarigan AKM, Bayer SB, Langhelle O, Thesen G. Estimating determinants of public acceptance of hydrogen vehicles and refuelling stations in greater Stavanger. *Int J Hydrogen Energy* 2012;37:6063–73. <https://doi.org/10.1016/j.ijhydene.2011.12.138>.
- [49] Huijts NMA, Van Wee B. The evaluation of hydrogen fuel stations by citizens: The interrelated effects of socio-demographic, spatial and psychological variables. *Int J Hydrogen Energy* 2015;40:10367–81. <https://doi.org/10.1016/j.ijhydene.2015.06.131>.
- [50] Yüksel YE. Elementary science teacher candidates' views on hydrogen as future energy carrier. *Int J Hydrogen Energy* 2019;44:9817–22. <https://doi.org/10.1016/j.ijhydene.2018.12.009>.
- [51] Eames M, McDowall W, Hodson M, Marvin S. Negotiating contested visions and place-specific expectations of the hydrogen economy. *Technol Anal Strateg Manag* 2006;18:361–74. <https://doi.org/10.1080/09537320600777127>.
- [52] Kheirandish S, Funk M, Wensveen S, Verkerk M, Rauterberg M. A comprehensive value framework for design. *Technol Soc* 2020;62:101302. <https://doi.org/10.1016/j.techsoc.2020.101302>.
- [53] Bouman T, van der Werff E, Perlaviciute G, Steg L. Environmental values and identities at the personal and group level. *Curr Opin Behav Sci* 2021;42:47–53. <https://doi.org/10.1016/j.cobeha.2021.02.022>.
- [54] Statistical Research and Training Institute MIC. Statistical Handbook of Japan 2022. Japan: 2022.
- [55] Tijdens K, Steinmetz S. Is the web a promising tool for data collection in developing countries? An analysis of the sample bias of 10 web and face-to-face surveys from Africa, Asia, and South America. *Int J Soc Res Methodol* 2016;19:461–79. <https://doi.org/10.1080/13645579.2015.1035875>.
- [56] New Energy and Industrial Technology Development Organization. Strategy for Developing Hydrogen and Fuel Cell Technologies. Kanagawa, Japan: 2020.
- [57] Entman RM. Framing: Toward Clarification of a Fractured Paradigm. *J Commun* 1993;43:51–8. <https://doi.org/https://doi.org/10.1111/j.1460-2466.1993.tb01304.x>.
- [58] McCarthy M, Brennan M, De Boer M, Ritson C. Media risk communication – what was said by whom and how was it interpreted. *J Risk Res* 2008;11:375–94. <https://doi.org/10.1080/13669870701566599>.
- [59] Chapman A, Okushima S. Engendering an inclusive low-carbon energy transition in Japan: Considering the perspectives and awareness of the energy poor. *Energy Policy* 2019;135:111017. <https://doi.org/10.1016/j.enpol.2019.111017>.
- [60] Hargreaves T, Nye M, Burgess J. Making energy visible: A qualitative field study of how householders interact with feedback from smart energy monitors. *Energy Policy* 2010;38:6111–9. <https://doi.org/10.1016/j.enpol.2010.05.068>.
- [61] CMS. The Promise of Hydrogen : An International Guide. Frankfurt, Germany: 2020.
- [62] New Energy and Industrial Technology Development Organization. Survey to improve social acceptance of hydrogen 2019. Kanagawa, Japan: 2020.
- [63] Sim M, Kim CS, Shon WJ, Lee YK, Choi EY, Shin DM. Hydrogen-rich water reduces inflammatory responses and prevents apoptosis of peripheral blood cells in healthy adults: a randomized, double-blind,

- controlled trial. *Sci Rep* 2020;10:2–11. <https://doi.org/10.1038/s41598-020-68930-2>.
- [64] IEA. *Global Hydrogen Review 2021*. 2021. <https://doi.org/10.1787/39351842-en>.
- [65] Klick H, Smith ERAN. Public understanding of and support for wind power in the United States. *Renew Energy* 2010;35:1585–91. <https://doi.org/10.1016/j.renene.2009.11.028>.
- [66] Okorie N, Ojebuyi BR, Macharia JW. *Global Impact of Media on Migration Issues*. IGI Global; 2019.
- [67] Junsheng H, Akhtar R, Masud MM, Rana MS, Banna H. The role of mass media in communicating climate science: An empirical evidence. *J Clean Prod* 2019;238:117934. <https://doi.org/10.1016/j.jclepro.2019.117934>.
- [68] Overhyping hydrogen as a fuel risks endangering net-zero goals. *Nature* 2022;611:426. <https://doi.org/10.1038/d41586-022-03693-6>.
- [69] Le ST, Nguyen TN, Linforth S, Ngo TD. Safety investigation of hydrogen energy storage systems using quantitative risk assessment. *Int J Hydrogen Energy* 2023;48:2861–75. <https://doi.org/10.1016/j.ijhydene.2022.10.082>.
- [70] Ballard. *Hydrogen Facts*. Burnaby, Canada: n.d.
- [71] Gallo M, Marinelli M. The Use of Hydrogen for Traction in Freight Transport: Estimating the Reduction in Fuel Consumption and Emissions in a Regional Context. *Energies* 2023;16. <https://doi.org/10.3390/en16010508>.
- [72] Martens C, Wilthaner M. *Unlocking hydrogen ’s power for long-haul freight transport*. New York: n.d.
- [73] Bockris JOM. The origin of ideas on a Hydrogen Economy and its solution to the decay of the environment. *Int J Hydrogen Energy* 2002;27:731–40. [https://doi.org/10.1016/S0360-3199\(01\)00154-9](https://doi.org/10.1016/S0360-3199(01)00154-9).