

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

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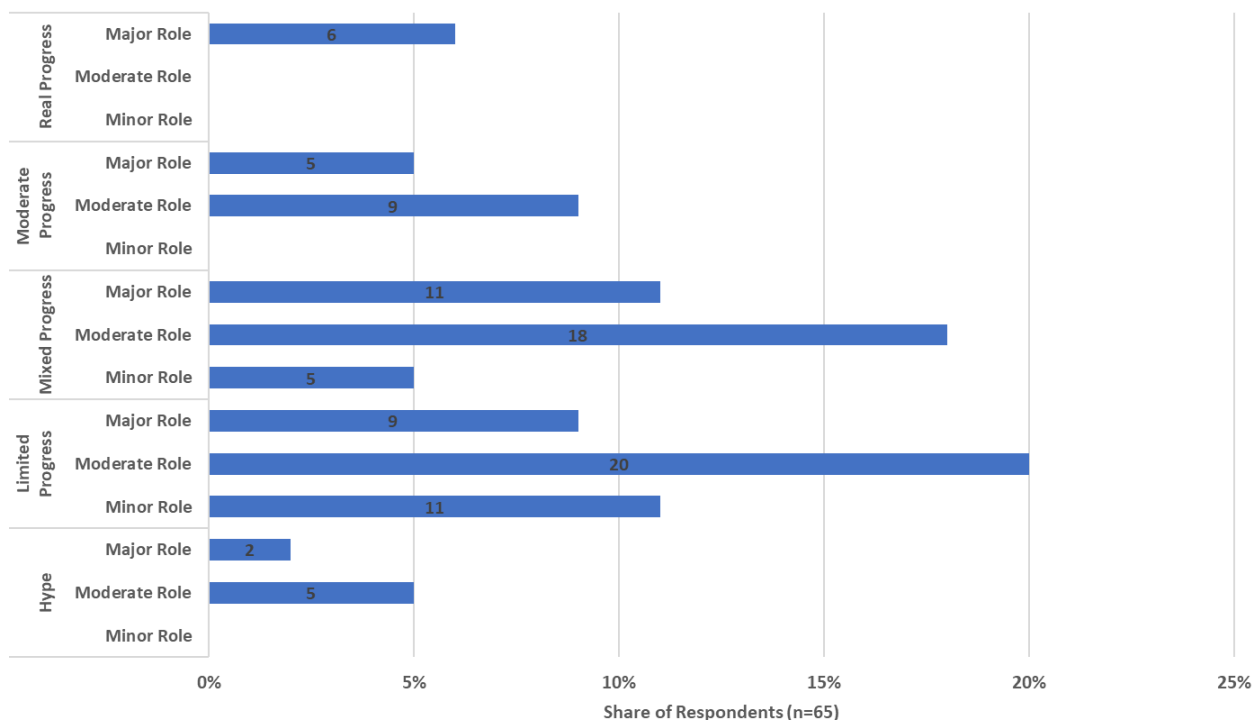
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Abstract

This study examines perspectives on the transition to a hydrogen economy, incorporating views from 65 experts across 22 countries. The results are categorized based on the experts' experience levels, the net energy import or export status of their respective countries, and by contrasting perspectives from both past and present. Amid intensified efforts to combat climate change, nations are shifting towards carbon neutrality, rekindling interest in a hydrogen-based energy system. Despite past waves of interest in hydrogen that have not seemingly produced progress, experts anticipate a significant future role for hydrogen, spurred by strategic initiatives and technological progress. They expect the emergence of a hydrogen trade landscape, akin to the fossil fuel market, with countries acting as exporters, importers, or transit hubs. In the short term, experts are divided on the preferred hydrogen method. However, in the middle and long term, there is a clear consensus among experts that the transition should move 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.

Graphical Abstract



Keywords: Hydrogen Economy, Expert Survey, Drivers, Barriers, Policy

1. Introduction

As global efforts intensify to limit anthropogenic climate change [1], there has been a worldwide shift towards carbon neutrality [2,3]. This involves a combination of initiatives such as reducing greenhouse gas emissions [3], transitioning to renewable energy sources [4], implementing carbon capture technologies [5], and promoting sustainable practices among both industries and individuals [6]. 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 [7]. However, achieving this will require decarbonization across various sectors [8,9], including power [10], transportation [11], buildings [12], and industry [13].

Given its versatility in various sectors, hydrogen is a potential option for decarbonization. While not new [14], it has garnered significant attention again in recent years [15]. The prospect of a hydrogen economy has been incorporated into national energy policies in numerous countries [16]. Yet, the interpretation and proposed implementation of hydrogen varies significantly from one country to another [17]. For instance, Japan has incorporated the prospect of a hydrogen economy into its national energy policy [18], seeing hydrogen as a means to achieve carbon neutrality by 2050. In contrast, Australia perceives hydrogen differently, viewing it mainly as an export commodity [19], 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 [20], others see it as a strategic resource to store excess renewable energy [21], and some emphasize its role in transitioning towards a greener transportation sector [22].

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 [23,24], it is important to recognize that most previously declared milestones have been missed [25,26], and the pace of progress has been slower than initially anticipated [27]. 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.

1.1. Research Aim

The aim of this study 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 is part of a parallel study with a community survey in Japan [25]. 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 [14]. 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 [28], which promotes an equitable transition towards a sustainable energy system, referred to as a just hydrogen economy [29,30].

The remainder of this paper is structured as follows. Section 2 provides the background, including a summary of the available expert surveys on hydrogen. Section 3 presents the methodology used, and Section 4 discusses the survey results. The final section summarizes the main conclusions and recommends policy actions.

2. Literature Review

In recent years, a growing body of literature has examined community stakeholders' experiences [31,32], perceptions and expectations regarding the development of the hydrogen economy [33–35]. 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 Tables 1 to 3 and the sections below. 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.

Insights from Hydrogen Economy Studies in National Context

The first set of thematic papers relate to national-level studies in specific countries. Table 1 summarizes these studies, which focus on future expectations, characteristics, socially integrated risks, and stakeholder perspectives in various countries.

Table 1: 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	[36]
2016*	Hydrogen Economy	Identify characteristics of hydrogen economy in China and recommend strategies for advancing its progress	[37]
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	[38]

2022*	Hydrogen Economy	Comprehend the perspective of the primary stakeholders of the hydrogen economy in Brazil	[39]
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The hydrogen economy has garnered increasing attention as a potentially sustainable alternative to traditional energy systems [40]. 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 [36] 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. [37] 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. [38] 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. [39] 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.

Insights from Hydrogen Production Studies

This section, starting with Table 2, summarizes key assessments of different production methods, benefits of cooperation, renewable hydrogen storage, and overcoming barriers to hydrogen technology deployment.

Table 2: 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	[41]
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	[42]
2016	Hydrogen Storage	Examines renewable hydrogen storage use in Europe, considering location, policy, and economic aspects to optimize storage amid fluctuating electricity demand	[43]
2017*	Hydrogen Infrastructure	Evaluates five non-economic barriers to the deployment of hydrogen technology in Europe, and propose appropriate measures to overcome them	[44]
2022	Hydrogen Production	To reach a basic agreement on strategically enabling large-scale green hydrogen demonstrations, followed by commercialization, in China	[45]

As the global interest in hydrogen production intensifies [46], 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. [42] 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. [41] 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. [45] 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. [43] 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 [44] 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.

Insights from Hydrogen End-Use Studies

The third thematic set of papers are summarized in Table 3. This section examines studies on fuel cell technologies, implementation, and barriers to hydrogen-based end-use technologies, such as hydrogen transportation.

Table 3: 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	[47]
2008	Hydrogen Transportation Technology*	Determine barriers hindering the widespread adoption of hydrogen transportation technology in China, Japan, North America, and Europe	[48]
2021*	Fuel Cell Vehicles	Compare the drivers and barriers affecting the production and adoption of fuel cell vehicles and electric buses	[49]
2022*	Fuel Cell Technologies	Identify and categorize the barriers hindering the advancement of hydrogen fuel cell energy in South Korea	[50]

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

In recent years, fuel cell technology has been garnering increased interest among researchers [51], leading to numerous studies aimed at understanding the barriers and challenges that hinder its widespread adoption. In 2003, Kosugi et al. [47] 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. [48] 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 [49] 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. [50] 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.

Addressing Research Gaps and Multinational Perspectives on Hydrogen Economy Transition

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 [43,44] and Hart et al. [48] 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 [38,39,41]. Each expert brings a unique background and knowledge base, contributing to diverse perspectives on the structure and implementation of a hydrogen economy [52]. Furthermore, the discrepancies in projected timelines for the realization of the hydrogen economy, as identified in some studies we reviewed [39,47,48], 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 [26,53].

Lastly, while some studies have explored expert opinions on the drivers and barriers to hydrogen technology adoption [44,49,50], the dynamic nature of energy transition [54,55], including the emergence of a hydrogen economy, requires ongoing investigation. Factors such as technological advancements [56], policy changes [57,58], and shifts in public perception [59,60] 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. Therefore, our study seeks to explore these shifting factors through an expert survey, aiming to provide a comprehensive understanding of the evolving factors within the hydrogen economy.

3. 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 [61], 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 [16]. 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 [33,35], 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) [42]. The initial approach involved a prior systematic literature review conducted by the authors [52], 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 paper 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 paper as the second part of the research. Our research approach employed mixed methods [62,63], 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.

4. 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.

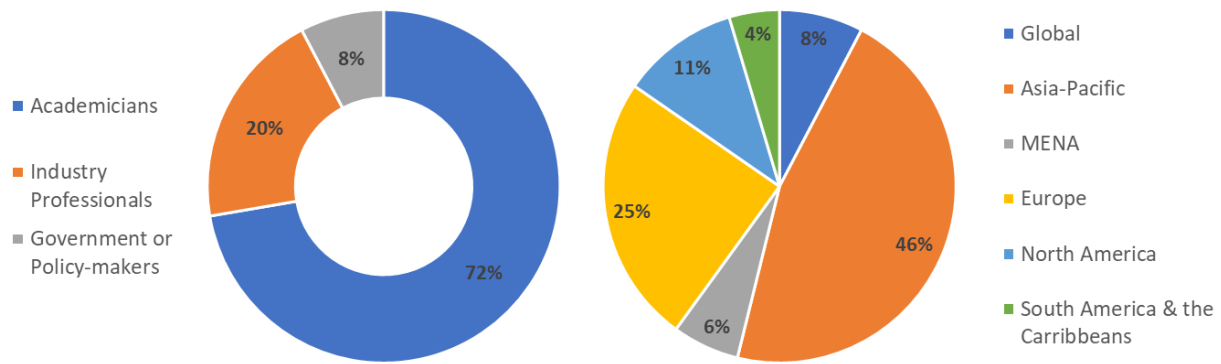


Figure 1: (Left) Expertise Breakdown of Respondents (Right) Regional distribution of knowledge on the Hydrogen Economy (n=65)

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.

As illustrated in Figure 1, 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 [16], 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.

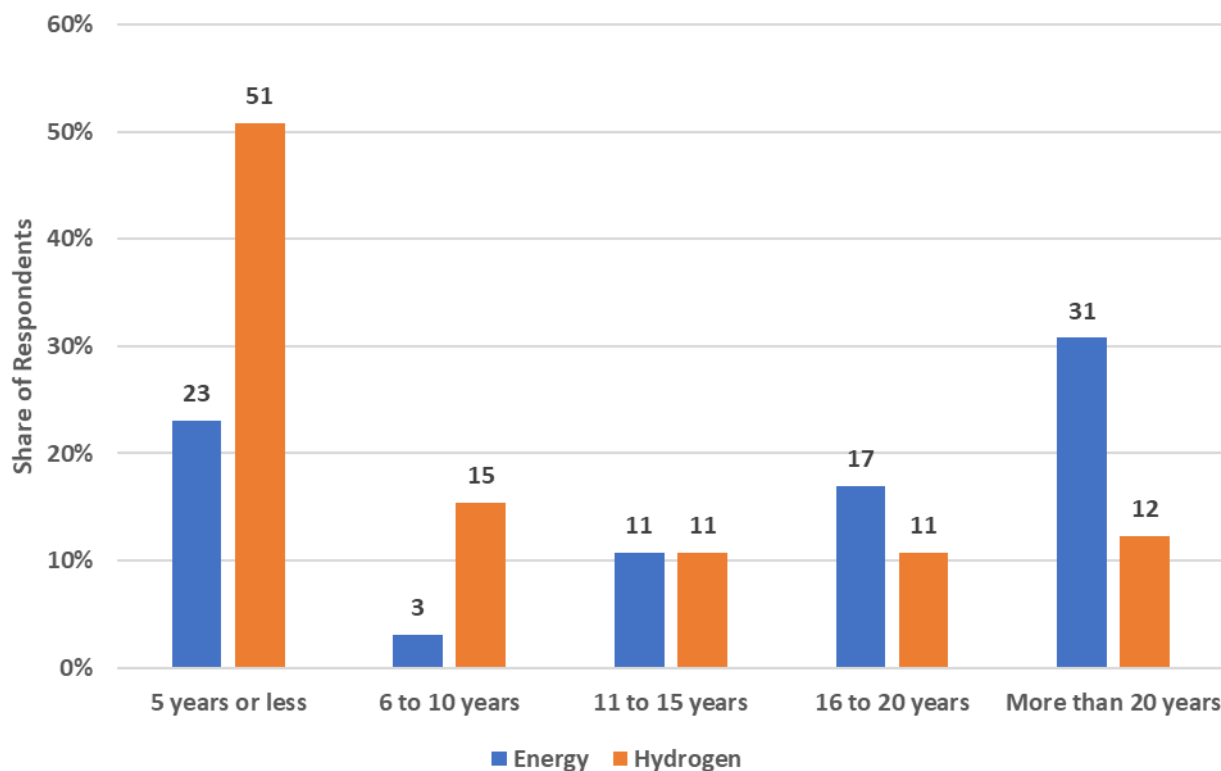


Figure 2: Comparison of experience levels in energy and hydrogen among respondents (n=65)

Figure 2 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 [52]. 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.

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 (as of 2023), and the expectation of its potential in the future.

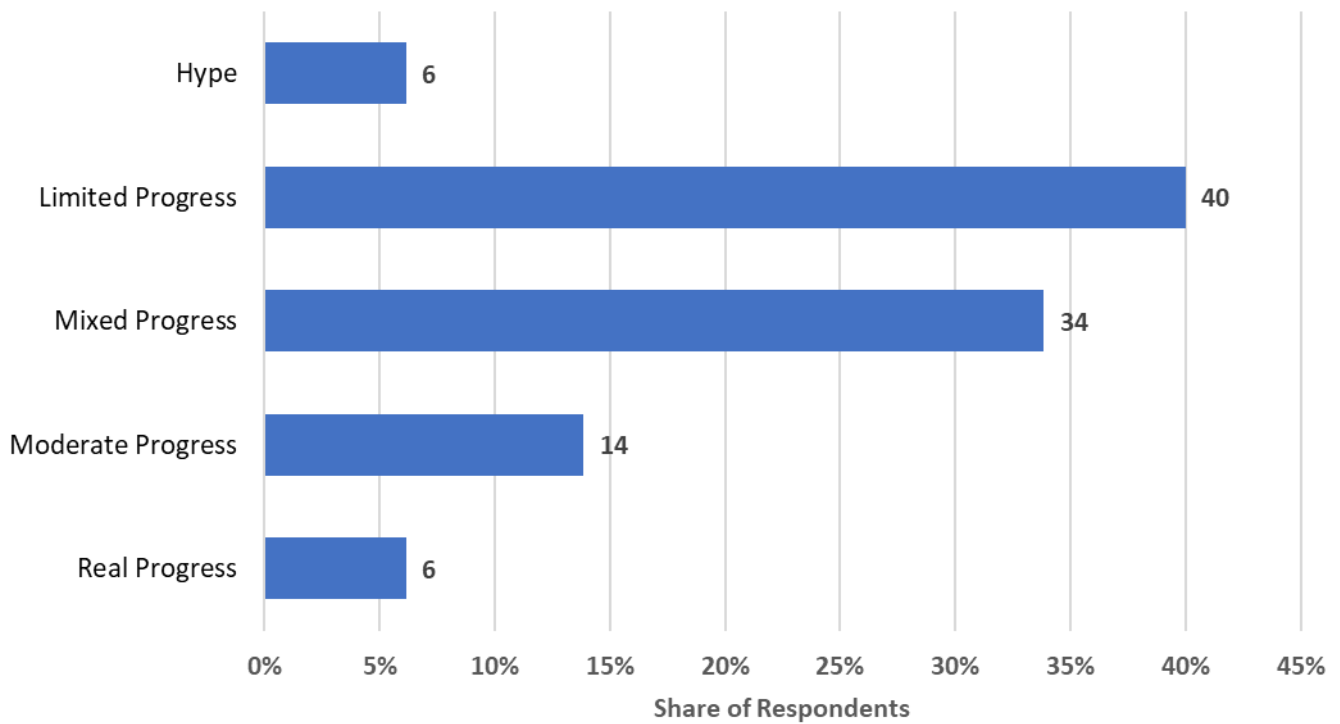


Figure 3: Evaluating progress of the hydrogen economy (n=65)

Figure 3 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 hold 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. While a small proportion see substantial progress or view current discussions as hype [64,65], the majority perceive progress as limited or mixed. **This perspective is supported by numerous studies mentioned in the literature review section, highlighting the gaps between hydrogen roadmap targets and the current state of hydrogen technology adoption. It's important to note that many set**

milestones have been missed, and progress has been slower than expected. This suggests that more work needs to be done for the hydrogen economy to fully realize its potential [66]. 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.

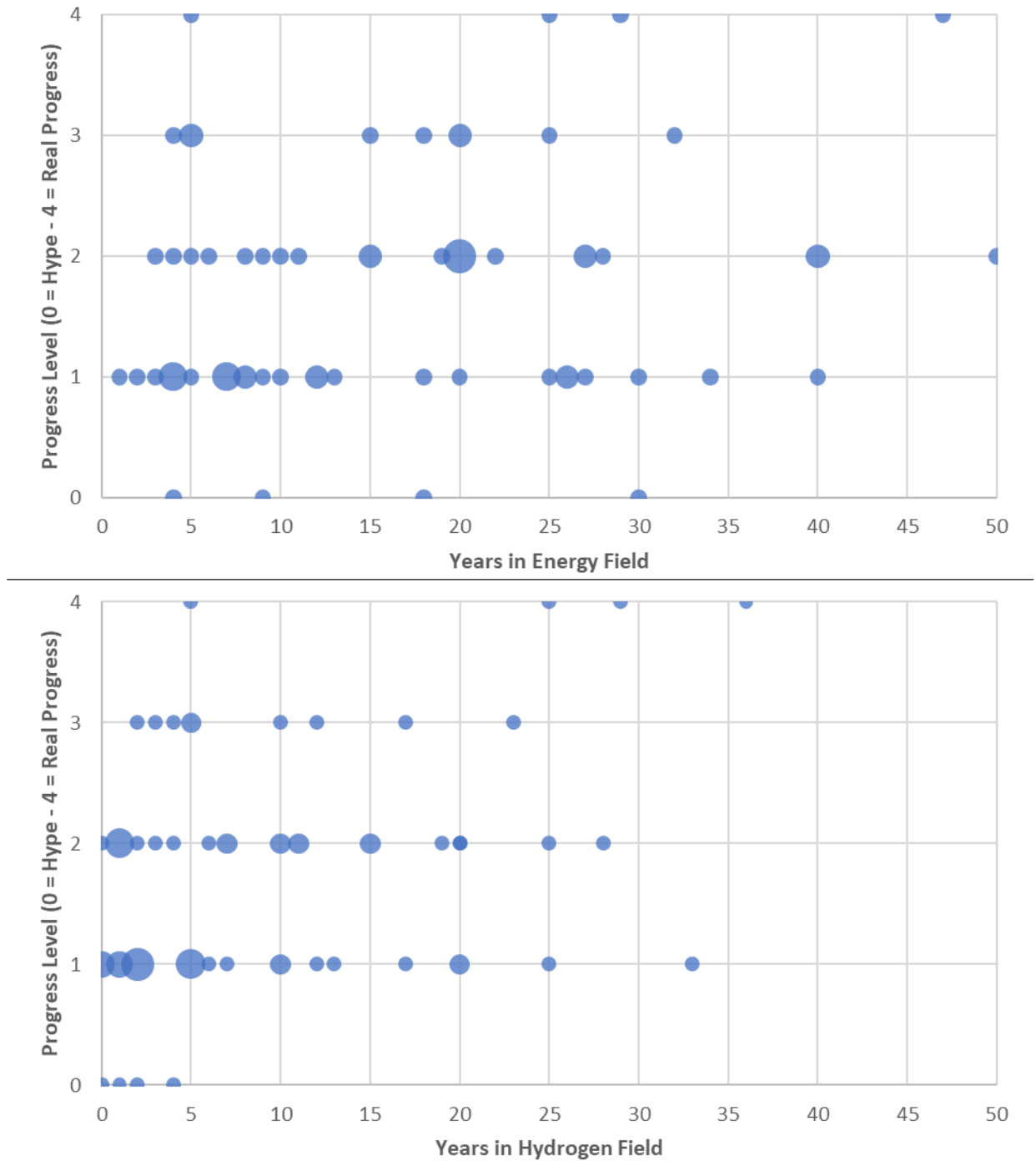


Figure 4: Experts` level of experience (energy (top) & hydrogen (bottom)) and perception of hydrogen economy progress (n=65)
(For this plot, the Progress Level was nominally allocated a number from 0 – Hype, 1 – Limited progress, 2 – Mixed progress, 3 – Moderate progress, 4 – Real progress)

In Figure 4, 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.

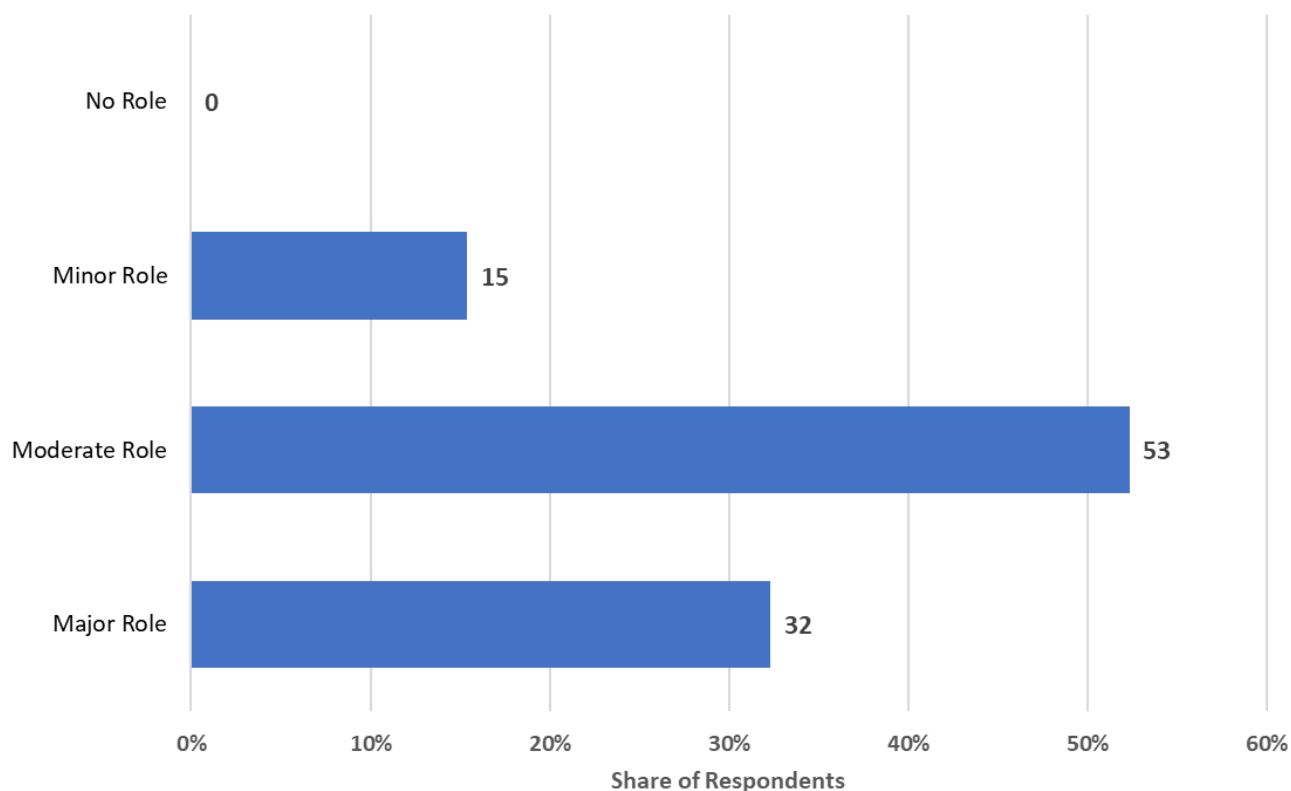


Figure 5: Evaluating the role of hydrogen in future by the year 2050 (n=65)

Figure 5 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, 53%, 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 [67]. 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 [68]. 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.

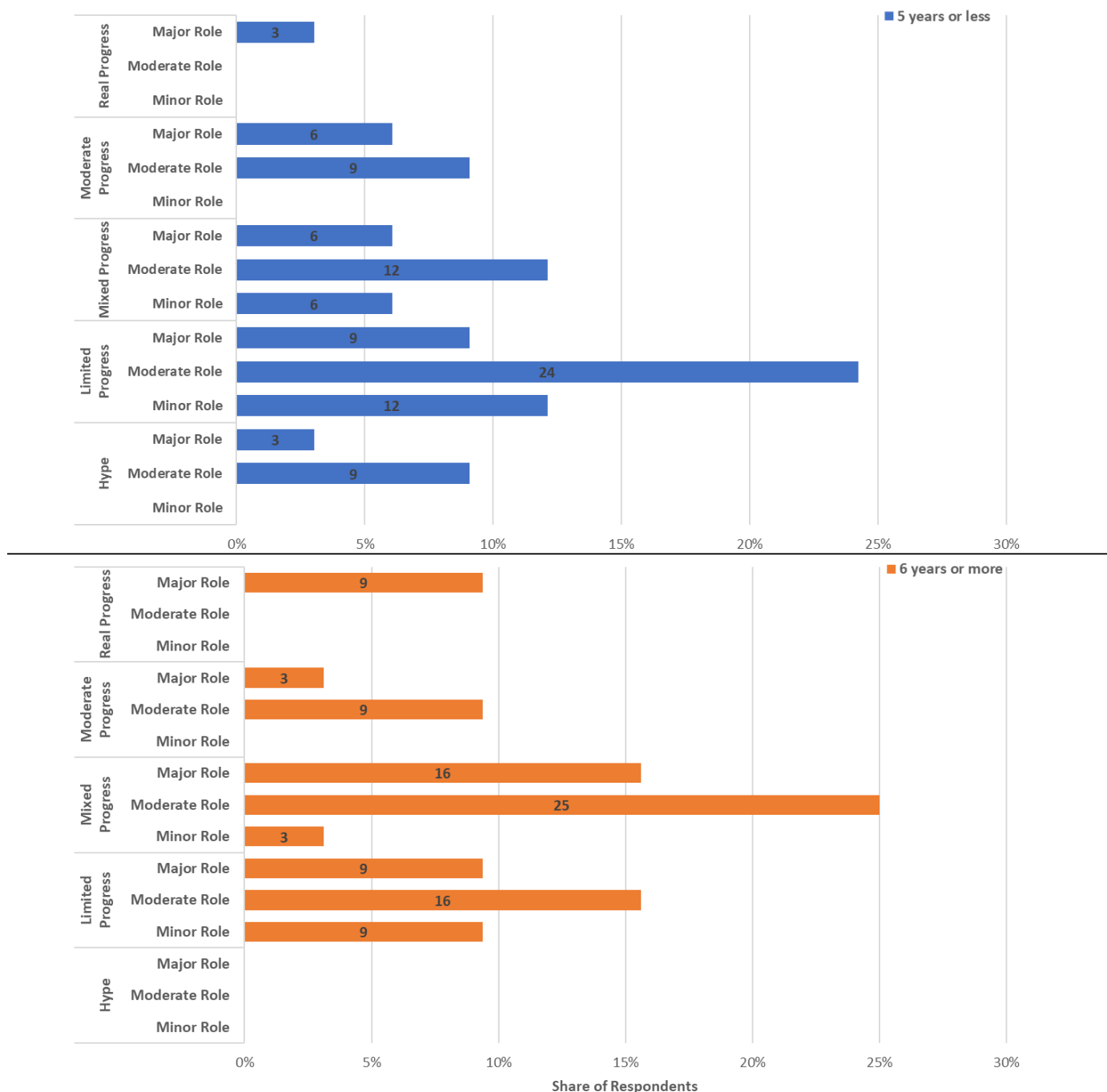


Figure 6: Current progress perspective versus future role of hydrogen and level of hydrogen experience (Top: Experts with 5 years or less experience (n=33) Bottom: Experts with 6 years or more experience (n=32))

Figure 6 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 two almost-equal groups. 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 [7]. None of the experts expect hydrogen to play no role in the future energy landscape (Figure 5). 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.

Hydrogen Supply Chain: Trade, Production, Key Role

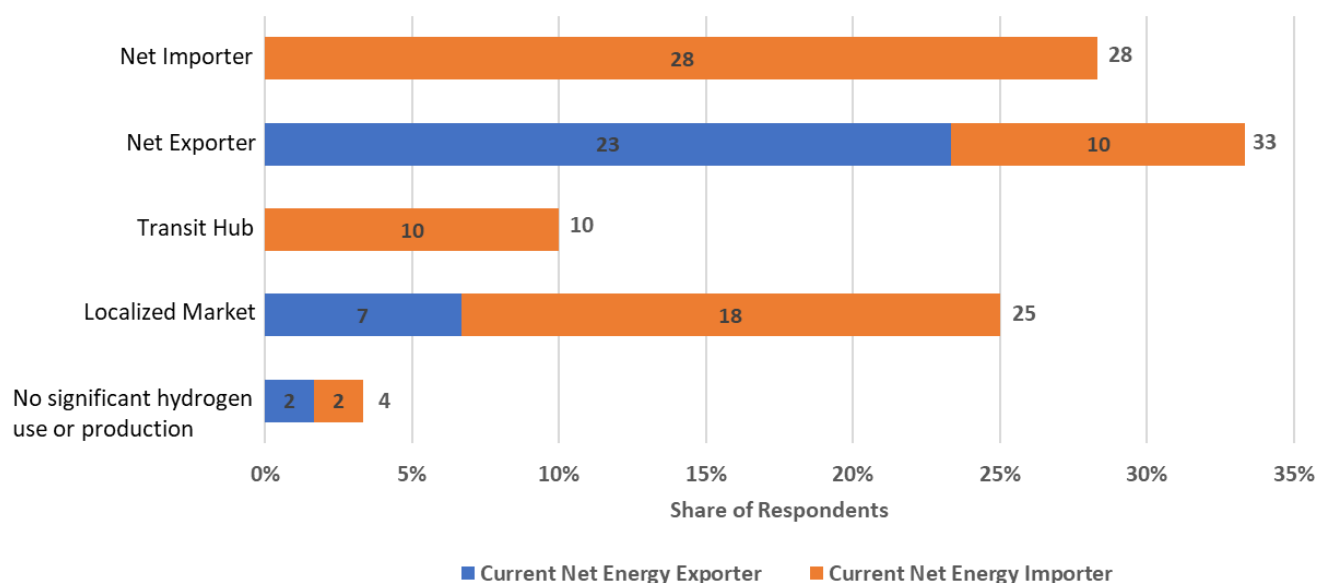


Figure 7: Status of countries as hydrogen develops into an internationally traded commodity (n=60)

Figure 7 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 analyze 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 [69] for the fiscal year 2020.

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. **However, achieving net exporter status in hydrogen not only requires technical and economic capabilities for large-scale hydrogen production but also reflects strategic decisions in energy policy. These countries face the critical challenge of balancing the national energy security with the opportunities presented by exporting hydrogen as a valuable commodity.** 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 [70]).

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, 18% of experts anticipate the emergence of localized hydrogen markets, higher than the 7% 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.

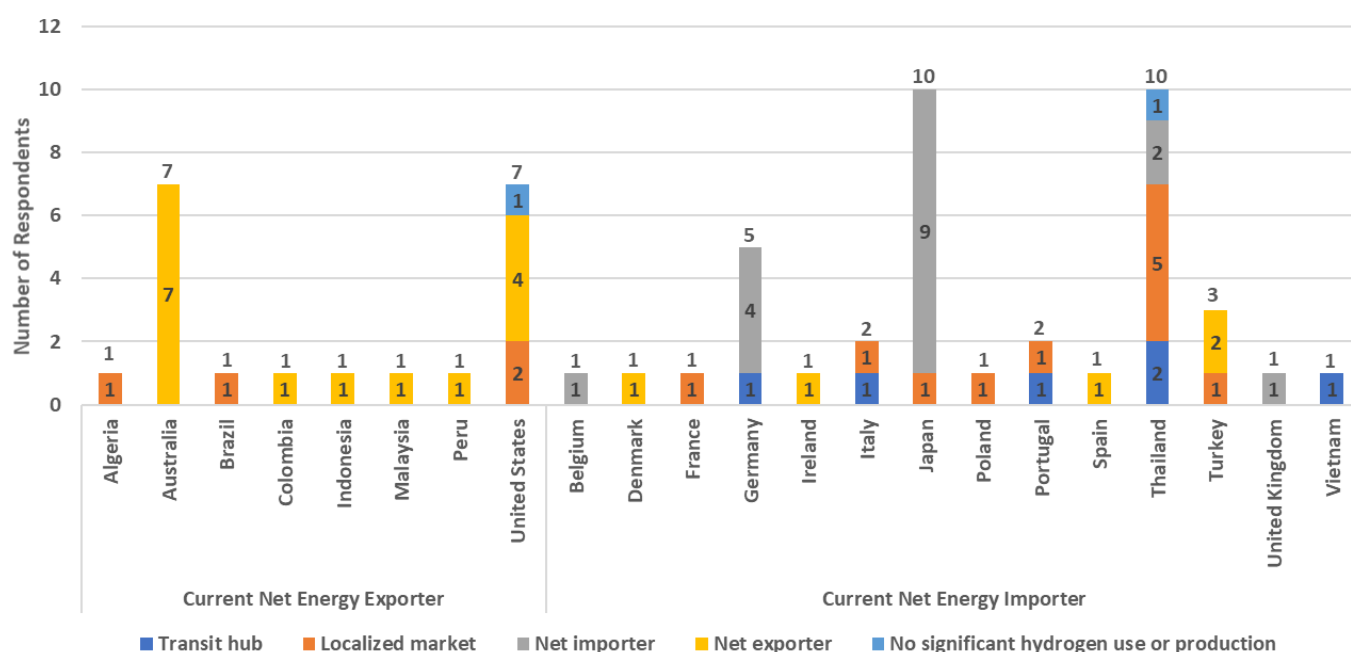


Figure 8: Classification of countries by net energy status in the emerging hydrogen trade (n=60)

Among the nations presented in Figure 8, 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 energy 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 [19,71]. 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 [18,72].

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. **This interest is rooted in their anticipation of substantial growth in renewable energy sectors, supportive policy frameworks, strategic geographical positioning, and technological innovations [17]. These countries are keenly aware of the potential of hydrogen as an export commodity and are positioning themselves not to miss out on this emerging opportunity in the transition towards a more sustainable energy-based global economy.** 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 8 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 7 and Figure 8 are meaningful in understanding the potential dynamics of the emerging global hydrogen economy [73]. 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 8).

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 [74]. 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 [75]. 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 [76]. 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.

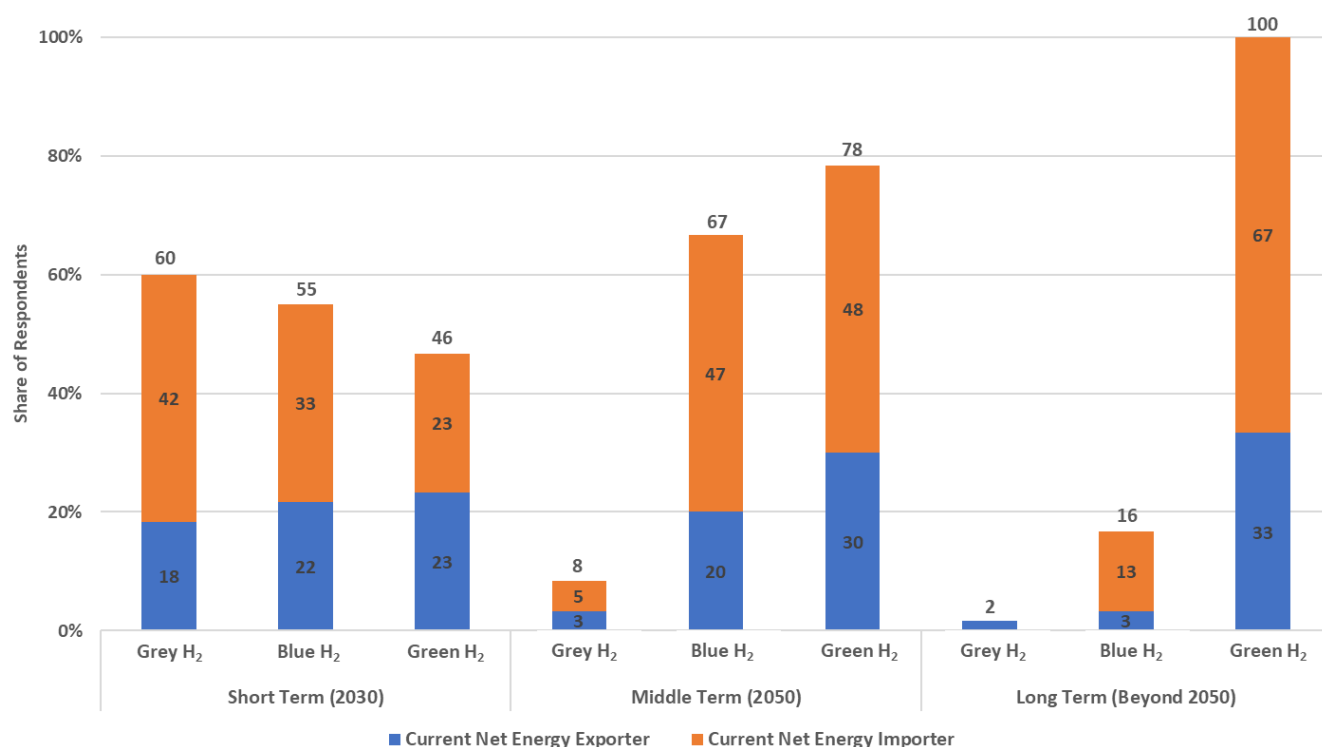


Figure 9: Expected hydrogen production by time horizon and level of hydrogen experience (n=60)

Figure 9 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 [77]) was the method expected to be most utilized with 60% of experts selecting it, closely followed by blue hydrogen (grey hydrogen with carbon capture and storage [77]) at 55%. Green hydrogen (produced through electrolysis of water using renewable energy [77]) 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's 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.

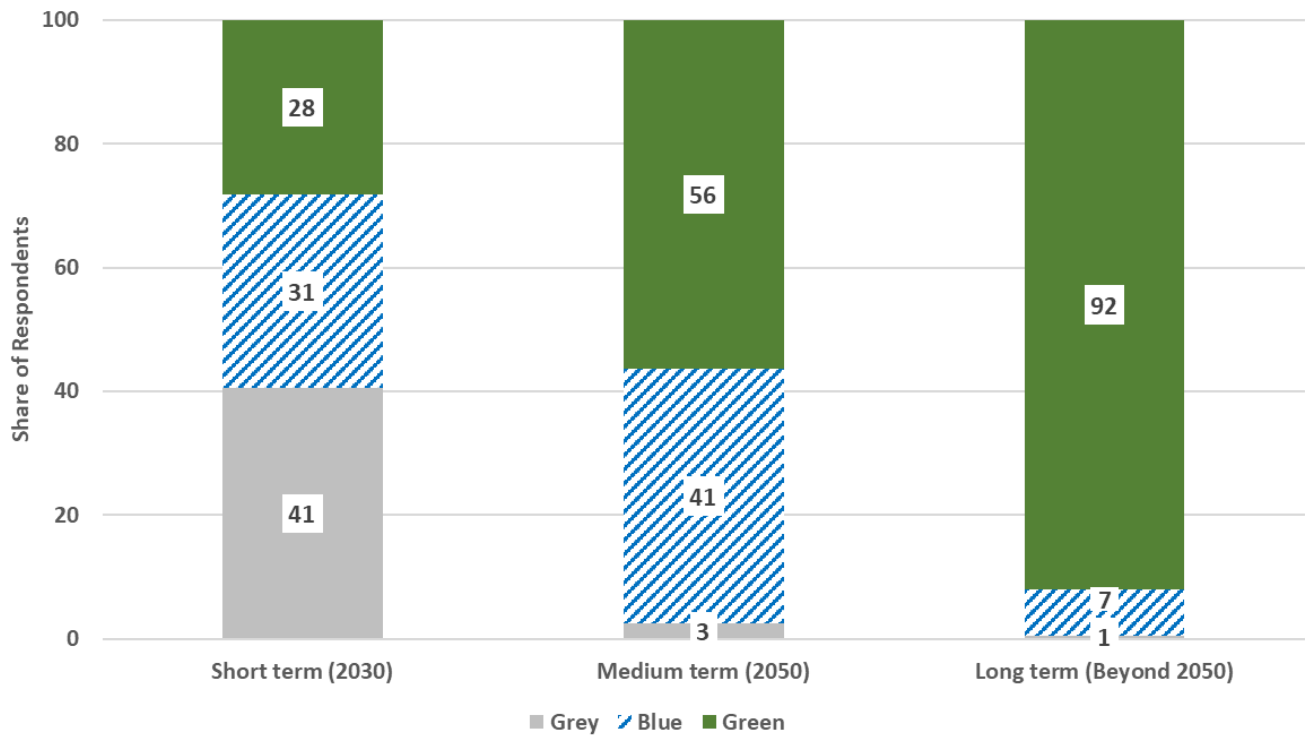


Figure 10: Expected change in hydrogen production (responses fractionally distributed across categories) (n=65)¹

Figure 10 presents expert opinions on the expected changes in hydrogen production across three timeframes, further highlighting a transition from grey to blue, and subsequently to green hydrogen [78]. 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 9 & Figure 10 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 [79], 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 [80]. 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 [81], potential technology lock-in

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)

of blue hydrogen production infrastructure [82], the infrastructure needs for green hydrogen [83], and the global climate targets [84].

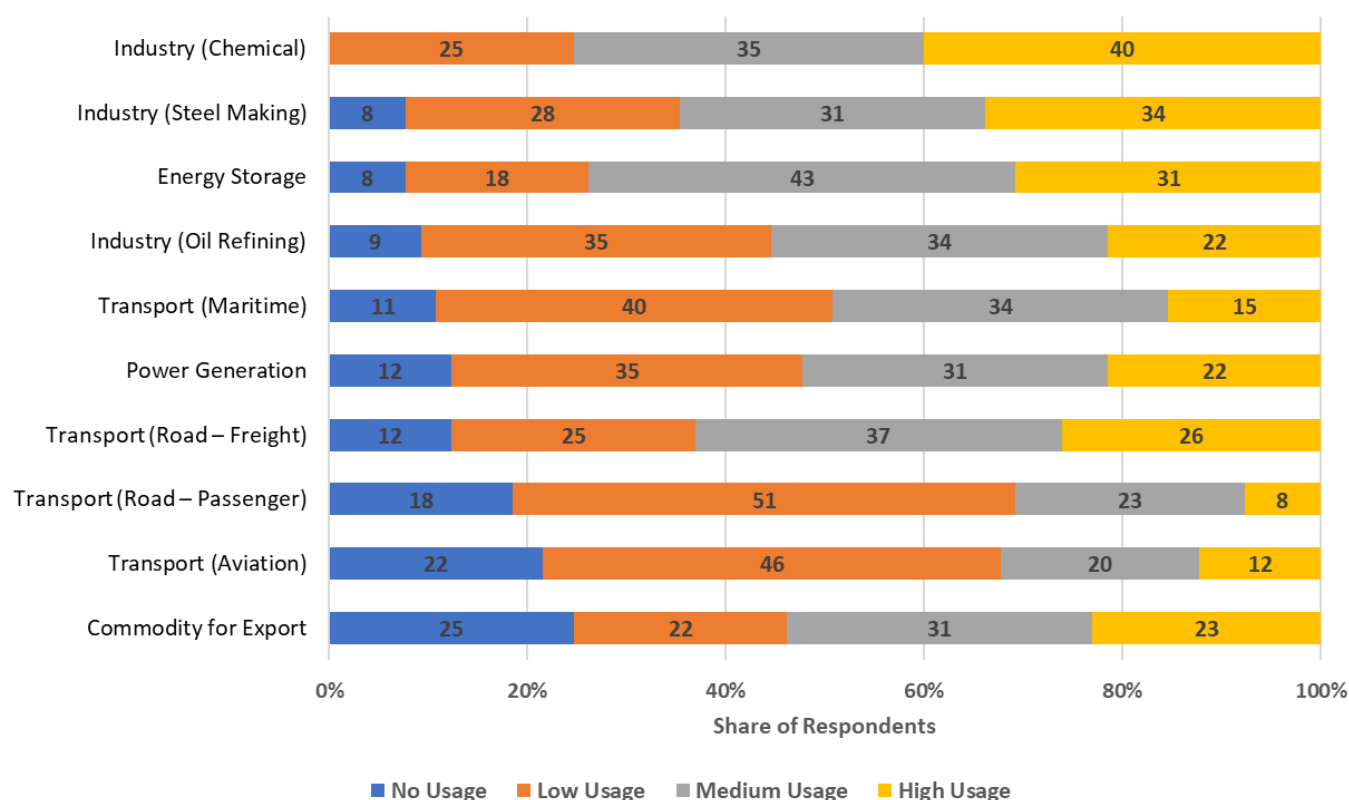


Figure 11: Key sectors in which experts envision hydrogen playing a key role (n=65)

Figure 11 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 [85], particularly in the production of ammonia for fertilizers and methanol. In the steel-making industry, a comparatively new role for hydrogen is emerging [86], 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 [87]. 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 [88]. 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 [89]. 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 [90].

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 [91]. 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) [92] 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 [91].

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 [93]. 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% [93]. 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 11 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 [16]. 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.

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

Figure 12 & Figure 13 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 four point 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 14 & Figure 15 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.

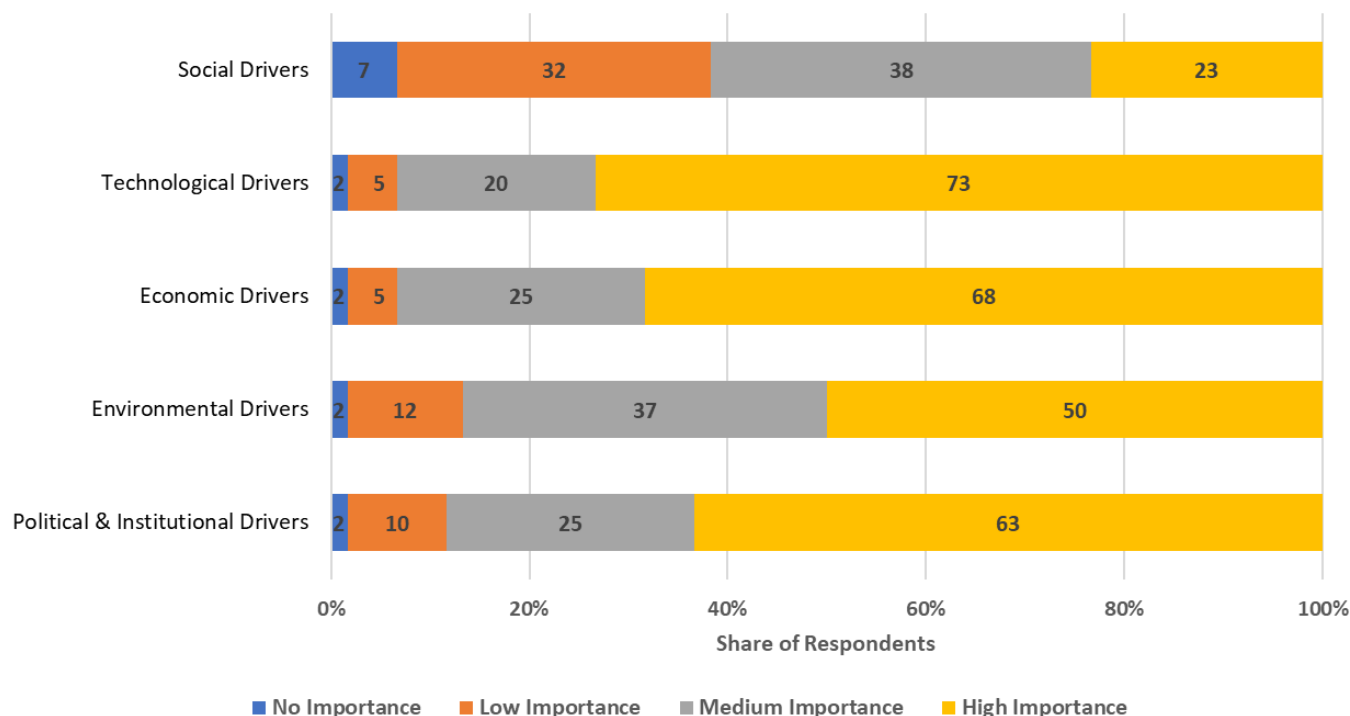


Figure 12: Importance of different drivers for developing a hydrogen economy (n=60)

In Figure 12, 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 [94,95]. It may also reflect the distribution of expertise among the experts – this could be further examined with the interview component of the research.

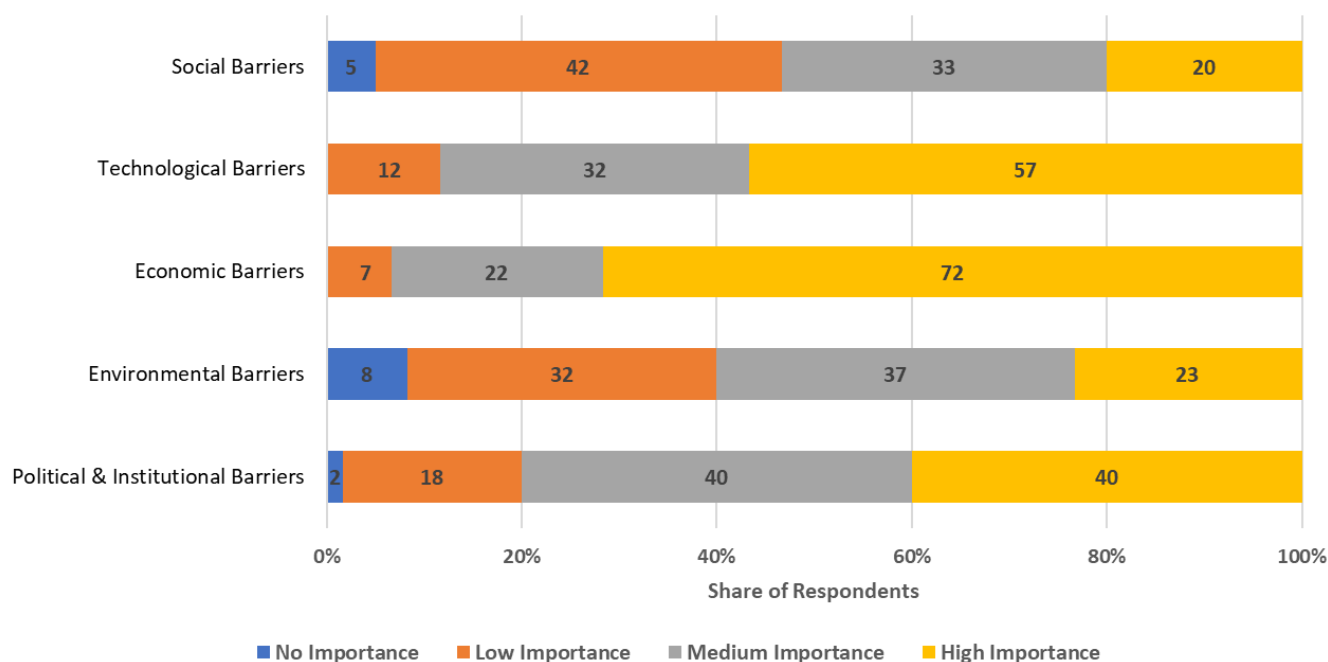


Figure 13: Importance of different barriers for developing hydrogen economy (n=60)

Figure 13 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 [96,97]. 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 [25].

Figure 12 & Figure 13 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.

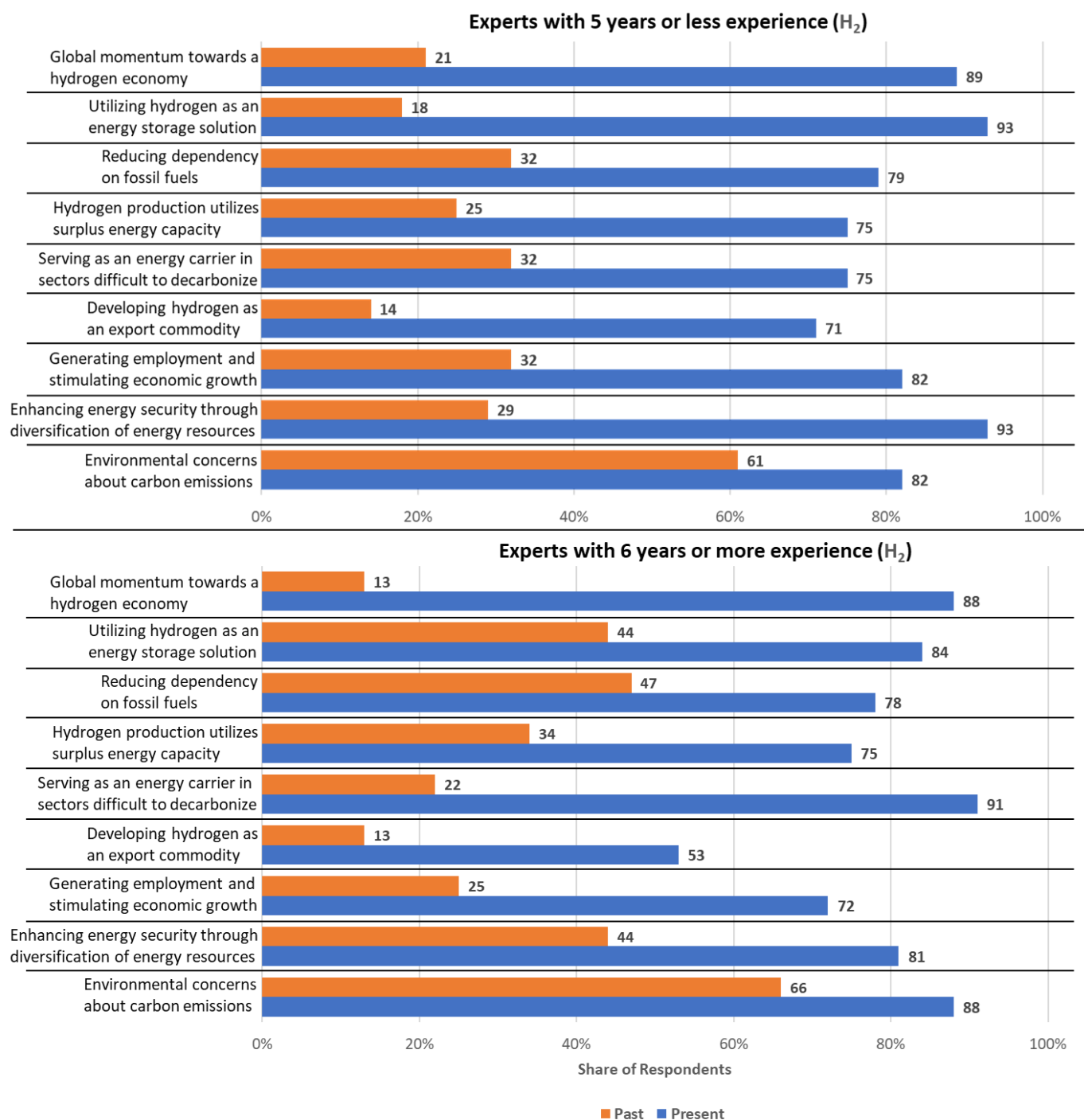


Figure 14: Comparison of past and present drivers for implementing a hydrogen economy (Top: Experts with 5 years or less experience (n=28) Bottom: Experts with 6 years or more experience (n=32))

Figure 14 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.

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 [98] and increasing pollution levels [99]. Hydrogen was identified as a potential solution to the global energy crisis in the 1970s [100,101], which encouraged the exploration of alternative technologies. It may be argued that the responses reflect these changing emphases.

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 [73], and a broad-based momentum towards hydrogen solutions [15].

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.

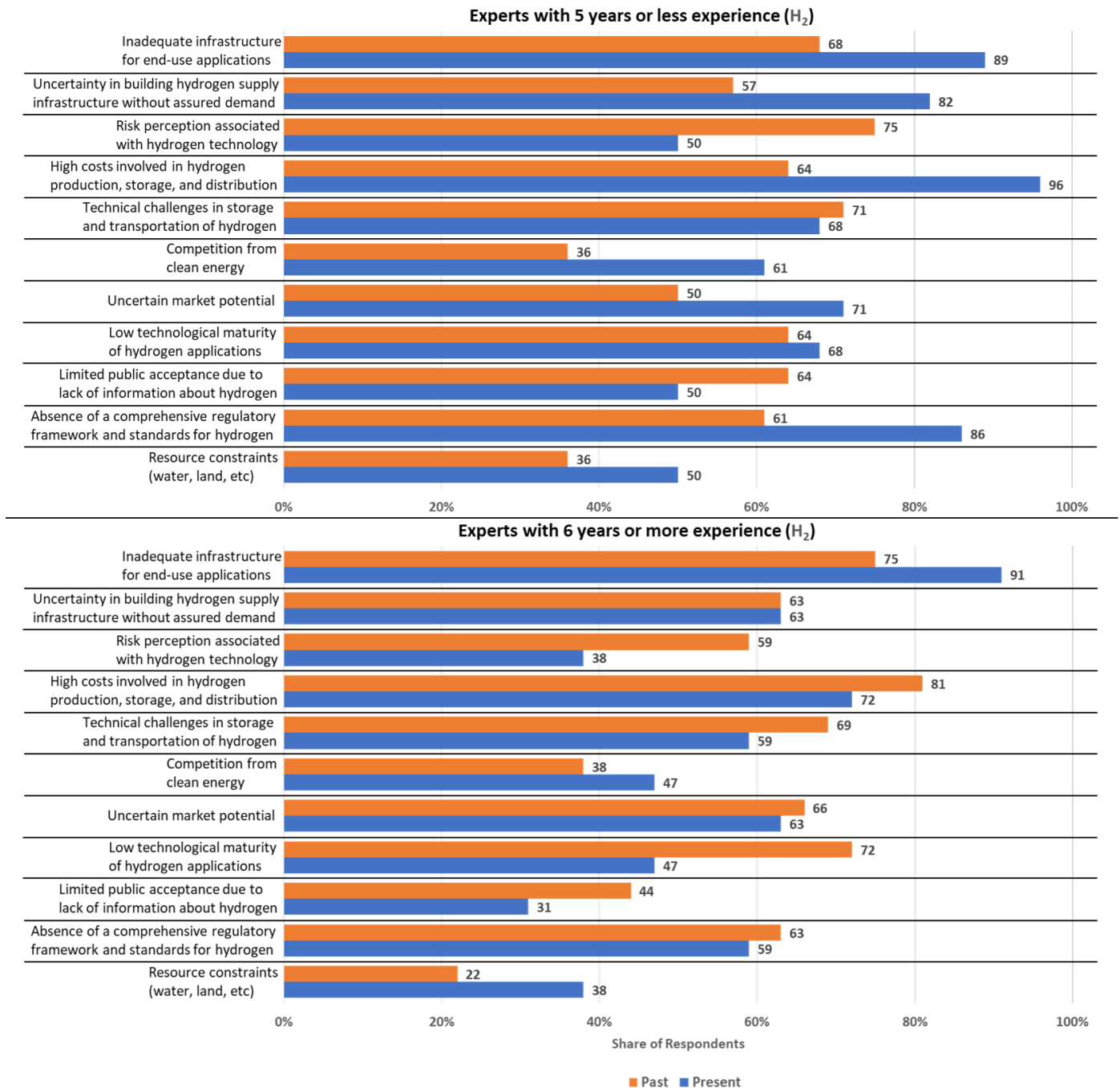


Figure 15: Comparison of past and present barriers for implementing a hydrogen economy (Top: Experts with 5 years or less experience (n=28) Bottom: Experts with 6 years or more experience (n=32))

Figure 15 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. 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 [15], the absence of necessary infrastructure is becoming more apparent [102,103], 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 [104] and knowledge about hydrogen [105], 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 15 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. 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 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 is unlikely to 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 prioritized 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 recommended.
- 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 persistent barriers and capitalize on hydrogen's unique potential. The result of this study is expected to instigate a dialogue that can 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.

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 [106] 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.

6. 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.

7. References

- [1] IPCC. Climate Change 2022: Impacts, Adaptation and Vulnerability. Cambridge, UK and New York, USA: Cambridge University Press; 2022.
- [2] Stern N, Valero A. Innovation , growth and the transition to net-zero emissions. *Res Policy* 2021;50:104293. <https://doi.org/10.1016/j.respol.2021.104293>.
- [3] Fankhauser S, Smith SM, Allen M, Axelsson K, Hale T, Hepburn C, et al. The meaning of net zero and how to get it right 2022;12:15–21. <https://doi.org/10.1038/s41558-021-01245-w>.
- [4] Renné DS. Progress , opportunities and challenges of achieving net-zero emissions and 100 % renewables 2022;1. <https://doi.org/10.1016/j.solcom.2022.100007>.
- [5] Gabrielli P, Gazzani M, Mazzotti M. The Role of Carbon Capture and Utilization , Carbon Capture and Storage , and Biomass to Enable a Net-Zero-CO₂ Emissions Chemical Industry 2020. <https://doi.org/10.1021/acs.iecr.9b06579>.
- [6] Shove E, Spurling N. Sustainable practices: Social theory and climate change. *Sustain. Pract.*, Routledge; 2013, p. 1–13.
- [7] IEA. Net Zero by 2050 A Roadmap for the Global Energy Sector. Paris: 2021.
- [8] IEA. World Energy Outlook 2022. Paris: 2022.
- [9] Papadis E, Tsatsaronis G. Challenges in the decarbonization of the energy sector. *Energy* 2020;205:118025. <https://doi.org/10.1016/j.energy.2020.118025>.
- [10] Strbac G, Papadaskalopoulos D, Chrysanthopoulos N, Estanqueiro A, Algarvio H, Lopes F, et al. Decarbonization of Electricity Systems in Europe: Market Design Challenges. *IEEE Power Energy Mag* 2021;19:53–63. <https://doi.org/10.1109/MPE.2020.3033397>.
- [11] Gota S, Huizenga C, Peet K, Medimorec N, Bakker S. Decarbonising transport to achieve Paris Agreement targets. *Energy Effic* 2019;12:363–86. <https://doi.org/10.1007/s12053-018-9671-3>.
- [12] Rosenbloom D, Levesque A, Pietzcker RC, Baumstark L, Luderer G. Deep decarbonisation of buildings energy services through demand and supply transformations in a OPEN ACCESS Deep decarbonisation of buildings energy services through demand and supply transformations in a 1.5 °C scenario 2021.
- [13] Napp TA, Gambhir A, Hills TP, Florin N, Fennell PS. A review of the technologies , economics and policy instruments for decarbonising energy-intensive manufacturing industries 2014;30:616–40. <https://doi.org/10.1016/j.rser.2013.10.036>.
- [14] 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).
- [15] IEA. Global Hydrogen Review 2021. 2021. <https://doi.org/10.1787/39351842-en>.
- [16] IRENA. Geopolitics of the Energy Transformation The Hydrogen Factor. Masdar, UAE: 2022.
- [17] World Energy Council. National Hydrogen Strategies 2021:1–20.
- [18] Government of Japan. Basic Hydrogen Strategy. 2017.
- [19] CSIRO. Australia National Hydrogen Roadmap. Canberra: 2018.
- [20] Hwang J, Maharjan K, Cho H. A review of hydrogen utilization in power generation and transportation sectors : Achievements and future challenges. *Int J Hydrogen Energy* 2023. <https://doi.org/10.1016/j.ijhydene.2023.04.024>.
- [21] Egeland-eriksen T, Hajizadeh A, Sartori S. Hydrogen-based systems for integration of renewable energy in power systems : Achievements and perspectives. *Int J Hydrogen Energy* 2021;46:31963–83. <https://doi.org/10.1016/j.ijhydene.2021.06.218>.
- [22] Manoharan Y, Hosseini SE, Butler B, Alzahrani H. Hydrogen Fuel Cell Vehicles ; Current Status and

Future Prospect 2019.

- [23] Nejat Veziroğlu T. Quarter century of hydrogen movement 1974–2000. *Int J Hydrogen Energy* 2000;25:1143–1150.
- [24] Bockris JOM. The hydrogen economy: Its history. *Int J Hydrogen Energy* 2013;38:2579–88. <https://doi.org/10.1016/j.ijhydene.2012.12.026>.
- [25] 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>.
- [26] 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>.
- [27] Institute RE. Re-examining Japan's Hydrogen Strategy: Moving Beyond the "Hydrogen Society" Fantasy. Tokyo: 2022.
- [28] Mccauley D, He R. Just transition : Integrating climate , energy and environmental justice. *Energy Policy* 2018;119:1–7. <https://doi.org/10.1016/j.enpol.2018.04.014>.
- [29] Scott M, Powells G. Towards a new social science research agenda for hydrogen transitions : Social practices , energy justice , and place attachment. *Energy Res Soc Sci* 2020;61:101346. <https://doi.org/10.1016/j.erss.2019.101346>.
- [30] Dillman KJ, Heinonen J. A ‘ just ’ hydrogen economy : A normative energy justice assessment of the hydrogen economy 2022;167.
- [31] Gordon JA, Balta-Ozkan N, Nabavi SA. Exploring the contours of consumer heterogeneity: Towards a typology of domestic hydrogen acceptance. *Energy Res Soc Sci* 2024;108:103401. <https://doi.org/10.1016/j.erss.2023.103401>.
- [32] Gordon JA, Balta-Ozkan N, Haq A, Nabavi SA. Coupling green hydrogen production to community benefits: a pathway to social acceptance. *Energy Res Soc Sci* 2024;110:103437. <https://doi.org/10.1016/j.erss.2024.103437>.
- [33] 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>.
- [34] 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>.
- [35] 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>.
- [36] Celiktaş MS, Kocar G. Hydrogen is not an utopia for Turkey. *Int J Hydrogen Energy* 2010;35:9–18. <https://doi.org/10.1016/j.ijhydene.2009.10.067>.
- [37] Ren J, Gao S, Tan S, Dong L. Hydrogen economy in China: Strengths-weaknesses-opportunities-threats analysis and strategies prioritization. *Renew Sustain Energy Rev* 2015;41:1230–43. <https://doi.org/10.1016/j.rser.2014.09.014>.
- [38] Hienuki S, Noguchi K, Shibutani T, Fuse M, Noguchi H, Miyake A. Risk identification for the introduction of advanced science and technology: A case study of a hydrogen energy system for smooth social implementation. *Int J Hydrogen Energy* 2020;45:15027–40. <https://doi.org/10.1016/j.ijhydene.2020.03.234>.
- [39] Chantre C, Andrade Elizário S, Pradelle F, Católico AC, Branquinho Das Dores AM, Torres Serra E, et al. Hydrogen economy development in Brazil: An analysis of stakeholders' perception. *Sustain Prod Consum*

2022;34:26–41. <https://doi.org/10.1016/j.spc.2022.08.028>.

- [40] Staffell I, Scamman D, Velazquez Abad A, Balcombe P, Dodds PE, Ekins P, et al. The role of hydrogen and fuel cells in the global energy system. *Energy Environ Sci* 2019;12:463–91. <https://doi.org/10.1039/c8ee01157e>.
- [41] Chung Y, Hong S, Kim J. Which of the technologies for producing hydrogen is the most prospective in Korea?: Evaluating the competitive priority of those in near-, mid-, and long-term. *Energy Policy* 2014;65:115–25. <https://doi.org/10.1016/j.enpol.2013.10.020>.
- [42] Enevoldsen P, Sovacool BK, Tambo T. Collaborate, involve, or defend? A critical stakeholder assessment and strategy for the Danish hydrogen electrolysis industry. *Int J Hydrogen Energy* 2014;39:20879–87. <https://doi.org/10.1016/j.ijhydene.2014.10.035>.
- [43] Garcia DA, Barbanera F, Cumo F, Di Matteo U, Nastasi B. Expert opinion analysis on renewable hydrogen storage systems potential in Europe. *Energies* 2016;9. <https://doi.org/10.3390/en9110963>.
- [44] Astiaso Garcia D. Analysis of non-economic barriers for the deployment of hydrogen technologies and infrastructures in European countries. *Int J Hydrogen Energy* 2017;42:6435–47. <https://doi.org/10.1016/j.ijhydene.2017.01.201>.
- [45] Li Y, Shi X, Phoumin H. A strategic roadmap for large-scale green hydrogen demonstration and commercialisation in China: A review and survey analysis. *Int J Hydrogen Energy* 2022;47:24592–609. <https://doi.org/10.1016/j.ijhydene.2021.10.077>.
- [46] Agyekum EB, Nutakor C, Agwa AM, Kamel S. A Critical Review of Renewable Hydrogen Production Methods: Factors Affecting Their Scale-Up and Its Role in Future Energy Generation. *Membranes (Basel)* 2022;12. <https://doi.org/10.3390/membranes12020173>.
- [47] Kosugi T, Hayashi A, Tokimatsu K. Forecasting development of elemental technologies and effect of R&D investments for polymer electrolyte fuel cells in Japan. *Int J Hydrogen Energy* 2004;29:337–46. <https://doi.org/10.1016/j.ijhydene.2003.08.001>.
- [48] Hart D, Anghel AT, Huijsmans J, Vuille F. A quasi-Delphi study on technological barriers to the uptake of hydrogen as a fuel for transport applications-Production, storage and fuel cell drivetrain considerations. *J Power Sources* 2009;193:298–307. <https://doi.org/10.1016/j.jpowsour.2008.12.122>.
- [49] Trencher G, Edianto A. Drivers and barriers to the adoption of fuel cell passenger vehicles and buses in Germany. *Energies* 2021;14. <https://doi.org/10.3390/en14040833>.
- [50] Lee Y, Lee MC, Kim YJ. Barriers and strategies of hydrogen fuel cell power generation based on expert survey in South Korea. *Int J Hydrogen Energy* 2022;47:5709–19. <https://doi.org/10.1016/j.ijhydene.2021.11.212>.
- [51] Yonoff RE, Ochoa GV, Cardenas-Escorcia Y, Silva-Ortega JI, Meriño-Stand L. Research trends in proton exchange membrane fuel cells during 2008–2018: A bibliometric analysis. *Heliyon* 2019;5. <https://doi.org/10.1016/j.heliyon.2019.e01724>.
- [52] 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>.
- [53] Trencher G. Strategies to accelerate the production and diffusion of fuel cell electric vehicles: Experiences from California. *Energy Reports* 2020;6:2503–19. <https://doi.org/10.1016/j.egyr.2020.09.008>.
- [54] Fouquet R, Pearson PJG. Past and prospective energy transitions: Insights from history. *Energy Policy* 2012;50:1–7. <https://doi.org/10.1016/j.enpol.2012.08.014>.
- [55] Grubler A. Energy transitions research: Insights and cautionary tales. *Energy Policy* 2012;50:8–16. <https://doi.org/10.1016/j.enpol.2012.02.070>.

- [56] Sinigaglia T, Freitag TE, Kreimeier F, Martins MES. Use of patents as a tool to map the technological development involving the hydrogen economy. *World Pat Inf* 2019;56:1–8. <https://doi.org/10.1016/j.wpi.2018.09.002>.
- [57] Burke MJ, Stephens JC. Political power and renewable energy futures: A critical review. *Energy Res Soc Sci* 2018;35:78–93. <https://doi.org/10.1016/j.erss.2017.10.018>.
- [58] Houghton T, Cruden A. Exploring future hydrogen development and the impact of policy: A novel investment-led approach. *Energy Policy* 2011;39:1318–29. <https://doi.org/10.1016/j.enpol.2010.12.004>.
- [59] Schönauer AL, Glanz S. Hydrogen in future energy systems: Social acceptance of the technology and its large-scale infrastructure. *Int J Hydrogen Energy* 2022;47:12251–63. <https://doi.org/10.1016/j.ijhydene.2021.05.160>.
- [60] 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>.
- [61] Krueger T, Page T, Hubacek K, Smith L, Hiscock K. The role of expert opinion in environmental modelling. *Environ Model Softw* 2012;36:4–18. <https://doi.org/10.1016/j.envsoft.2012.01.011>.
- [62] Beasy K, Emery S, Pryor K, Vo TA. Skilling the green hydrogen economy: A case study from Australia. *Int J Hydrogen Energy* 2023;48:19811–20. <https://doi.org/10.1016/j.ijhydene.2023.02.061>.
- [63] Creswell JW. *A Concise Introduction to Mixed Methods Research*. SAGE Publications; 2014.
- [64] Kriechbaum M, Posch A, Hauswiesner A. Hype cycles during socio-technical transitions: The dynamics of collective expectations about renewable energy in Germany. *Res Policy* 2021;50:104262. <https://doi.org/10.1016/j.respol.2021.104262>.
- [65] Dedehayir O, Steinert M. The hype cycle model: A review and future directions. *Technol Forecast Soc Change* 2016;108:28–41. <https://doi.org/10.1016/j.techfore.2016.04.005>.
- [66] IEA. *The Future of Hydrogen*. Paris: 2019.
- [67] Brandon NP, Kurban Z. Clean energy and the hydrogen economy. *Philos Trans R Soc A Math Phys Eng Sci* 2017;375. <https://doi.org/10.1098/rsta.2016.0400>.
- [68] IEA. *Global Hydrogen Review 2023*. Paris: 2023. <https://doi.org/10.1787/cb2635f6-en>.
- [69] IEA. *World Energy Balances 2021*. Paris: 2021.
- [70] Curtis AJ, Mclellan BC. Potential Domestic Energy System Vulnerabilities from Major Exports of Green Hydrogen : A Case Study of Australia 2023:1–34.
- [71] COAG Energy Council Hydrogen Working Group. *Australia National Hydrogen Strategy*. 2019.
- [72] Government of Japan. *Basic Hydrogen Strategy*. Tokyo: 2023.
- [73] Van de Graaf T, Overland I, Scholten D, Westphal K. The new oil? The geopolitics and international governance of hydrogen. *Energy Res Soc Sci* 2020;70:101667. <https://doi.org/10.1016/j.erss.2020.101667>.
- [74] Lo Faro M, Cantane DA, Naro F. In the path for creating Research-to-business new opportunities on green hydrogen between Italy and Brazil. *Int J Hydrogen Energy* 2022;48:11876–84. <https://doi.org/10.1016/j.ijhydene.2022.05.089>.
- [75] Chapman AJ, Fraser T, Itaoka K. Hydrogen import pathway comparison framework incorporating cost and social preference: Case studies from Australia to Japan. *Int J Energy Res* 2017;41:2374–91. <https://doi.org/10.1002/er.3807>.
- [76] IEA. *Towards hydrogen definitions based on their emissions intensity*. Paris: 2023.
- [77] Ji M, Wang J. Review and comparison of various hydrogen production methods based on costs and life cycle impact assessment indicators. *Int J Hydrogen Energy* 2021;46:38612–35.

- <https://doi.org/10.1016/j.ijhydene.2021.09.142>.
- [78] Espegren K, Damman S, Pisciella P, Graabak I, Tomasgard A. The role of hydrogen in the transition from a petroleum economy to a low-carbon society. *Int J Hydrogen Energy* 2021;46:23125–38. <https://doi.org/10.1016/j.ijhydene.2021.04.143>.
 - [79] George JF, Müller VP, Winkler J, Ragwitz M. Is blue hydrogen a bridging technology? - The limits of a CO₂ price and the role of state-induced price components for green hydrogen production in Germany. *Energy Policy* 2022;167:113072. <https://doi.org/10.1016/j.enpol.2022.113072>.
 - [80] Hermesmann M, Müller TE. Green, Turquoise, Blue, or Grey? Environmentally friendly Hydrogen Production in Transforming Energy Systems. *Prog Energy Combust Sci* 2022;90:100996. <https://doi.org/10.1016/j.pecs.2022.100996>.
 - [81] Wang X, Lo K. Just transition: A conceptual review. *Energy Res Soc Sci* 2021;82:102291. <https://doi.org/10.1016/j.erss.2021.102291>.
 - [82] Rosenow J, Lowes R. Will blue hydrogen lock us into fossil fuels forever? *One Earth* 2021;4:1527–9. <https://doi.org/10.1016/j.oneear.2021.10.018>.
 - [83] Hassan Q, Algburi S, Sameen AZ, Salman HM, Jaszczur M. Green hydrogen: A pathway to a sustainable energy future. *Int J Hydrogen Energy* 2024;50:310–33. <https://doi.org/10.1016/j.ijhydene.2023.08.321>.
 - [84] Programme UNE. Paris Agreement n.d.
 - [85] Ausfelder F, Bazzanella A. Hydrogen in the Chemical Industry. *Hydrog. Sci. Eng. Mater. Process. Syst. Technol.*, 2016, p. 19–40. <https://doi.org/https://doi.org/10.1002/9783527674268.ch02>.
 - [86] Vogl V, Åhman M, Nilsson LJ. Assessment of hydrogen direct reduction for fossil-free steelmaking. *J Clean Prod* 2018;203:736–45. <https://doi.org/10.1016/j.jclepro.2018.08.279>.
 - [87] Wang RR, Zhao YQ, Babich A, Senk D, Fan XY. Hydrogen direct reduction (H-DR) in steel industry—An overview of challenges and opportunities. *J Clean Prod* 2021;329. <https://doi.org/10.1016/j.jclepro.2021.129797>.
 - [88] Moradpoor I, Syri S, Santasalo-Aarnio A. Green hydrogen production for oil refining – Finnish case. *Renew Sustain Energy Rev* 2023;175:113159. <https://doi.org/10.1016/j.rser.2023.113159>.
 - [89] Hwang J, Maharjan K, Cho HJ. A review of hydrogen utilization in power generation and transportation sectors: Achievements and future challenges. *Int J Hydrogen Energy* 2023;48:28629–48. <https://doi.org/10.1016/j.ijhydene.2023.04.024>.
 - [90] Elberry AM, Thakur J, Veysey J. Seasonal hydrogen storage for sustainable renewable energy integration in the electricity sector: A case study of Finland. *J Energy Storage* 2021;44:103474. <https://doi.org/10.1016/j.est.2021.103474>.
 - [91] Martens C, Wilthaner M. Unlocking hydrogen ’s power for long-haul freight transport. New York: n.d.
 - [92] 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>.
 - [93] IRENA. Hydrogen: a Renewable Energy Perspective. Masdar, UAE: 2019.
 - [94] Gordon JA, Balta-Ozkan N, Nabavi SA. Homes of the future: Unpacking public perceptions to power the domestic hydrogen transition. *Renew Sustain Energy Rev* 2022;164:112481. <https://doi.org/10.1016/j.rser.2022.112481>.
 - [95] 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>.

- [96] Beswick RR, Oliveira AM, Yan Y. Does the Green Hydrogen Economy Have a Water Problem? *ACS Energy Lett* 2021;6:3167–9. <https://doi.org/10.1021/acsenergylett.1c01375>.
- [97] Tonelli D, Rosa L, Gabrielli P, Caldeira K, Parente A, Contino F. Global land and water limits to electrolytic hydrogen production using wind and solar resources. *Nat Commun* 2023;14:1–14. <https://doi.org/10.1038/s41467-023-41107-x>.
- [98] Bockris JOM. A hydrogen economy. *Science* (80-) 1972;176:1323. <https://doi.org/10.1126/science.176.4041.1323>.
- [99] Dickson EM, Ryan JW, Smulyan MH. Systems considerations and transition scenarios for the hydrogen economy. *Int J Hydrogen Energy* 1976;1:11–21. [https://doi.org/10.1016/0360-3199\(76\)90005-7](https://doi.org/10.1016/0360-3199(76)90005-7).
- [100] Schumacher D. The 1973 Oil Crisis and its Aftermath. *Energy Cris. or Oppor. An Introd. to Energy Stud.*, London: Macmillan Education UK; 1985, p. 21–41. https://doi.org/10.1007/978-1-349-17797-4_2.
- [101] Miller FP, Vandome AF, McBrewster J. 1970s Energy Crisis: Petroleum, 1973 Oil Crisis, 1979 Energy Crisis, Organization of Arab Petroleum Exporting Countries, Iranian Revolution, Middle East, Stagflation, Peak Oil, 1980s Oil Glut, 1973-75 Recession. Alphascript Publishing; 2009.
- [102] Riera JA, Lima RM, Knio OM. A review of hydrogen production and supply chain modeling and optimization. *Int J Hydrogen Energy* 2023;48:13731–55. <https://doi.org/10.1016/j.ijhydene.2022.12.242>.
- [103] Kurtz J, Sprik S, Bradley TH. Review of transportation hydrogen infrastructure performance and reliability. *Int J Hydrogen Energy* 2019;44:12010–23. <https://doi.org/10.1016/j.ijhydene.2019.03.027>.
- [104] Yue M, Lambert H, Pahon E, Roche R, Jemei S, Hissel D. Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renew Sustain Energy Rev* 2021;146:111180. <https://doi.org/10.1016/j.rser.2021.111180>.
- [105] 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>.
- [106] Hydrogen Economy Research n.d. https://eecon.energy.kyoto-u.ac.jp/en/?page_id=1030.