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

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Article

Opportunities and Challenges of Hydrogen Ports: An Empirical Study in Australia and Japan

Peggy Shu-Ling Chen ¹, Hongjun Fan ^{1,*}, Hossein Enshaei ¹, Wei Zhang ¹, Wenming Shi ¹,
Nagi Abdussamie ², Takashi Miwa ³, Zhuohua Qu ⁴ and Zaili Yang ⁵

- ¹ Australian Maritime College (AMC), College of Sciences and Engineering, University of Tasmania, Launceston, TAS 7248, Australia; p.chen@utas.edu.au (P.S.-L.C.); hossein.enshaei@utas.edu.au (H.E.); vera.zhang@utas.edu.au (W.Z.); wenming.shi@utas.edu.au (W.S.)
- ² College of Engineering & Technology, University of Doha for Science and Technology, Doha 24449, Qatar; nagi.abdussamie@udst.edu.qa
- ³ Faculty of Maritime Science, Kobe University, Kobe 658-0022, Japan; miwa@maritime.kobe-u.ac.jp
- ⁴ Liverpool Business School, Liverpool John Moores University, Liverpool L3 5UG, UK; z.qu@ljmu.ac.uk
- ⁵ Liverpool Logistics, Offshore and Marine Research Institute (LOOM), Liverpool John Moores University, Liverpool L3 3AF, UK; z.yang@ljmu.ac.uk
- * Correspondence: hongjun.fan@utas.edu.au

Abstract: This paper investigated the opportunities and challenges of integrating ports into hydrogen (H₂) supply chains in the context of Australia and Japan because they are leading countries in the field and are potential leaders in the upcoming large-scale H₂ trade. Qualitative interviews were conducted in the two countries to identify opportunities for H₂ ports, necessary infrastructure and facilities, key factors for operations, and challenges associated with the ports' development, followed by an online survey investigating the readiness levels of H₂ export and import ports. The findings reveal that there are significant opportunities for both countries' H₂ ports and their respective regions, which encompass business transition processes and decarbonisation. However, the ports face challenges in areas including infrastructure, training, standards, and social licence, and the sufficiency and readiness levels of port infrastructure and other critical factors are low. Recommendations were proposed to address the challenges and barriers encountered by H₂ ports. To optimise logistics operations within H₂ ports and facilitate effective integration of H₂ applications, this paper developed a user-oriented working process framework to provide guidance to ports seeking to engage in the H₂ economy. Its findings and recommendations contribute to filling the existing knowledge gap pertaining to H₂ ports.

Keywords: decarbonisation; energy; hydrogen; ammonia; methanol; liquid organic hydrogen carrier (LOHC); supply chain; H₂ port; shipping; bunkering



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1. Introduction

Sixteen out of the top twenty greenhouse gas (GHG)-emitting countries have clearly raised hydrogen (H₂) to the level of national energy strategies [1]. The worldwide H₂ demand and unbalanced H₂ production capacity drive the formation of international H₂ trade [2–4]. Therefore, the potential of H₂ supply chains is vast.

A typical international H₂ supply chain consists of production, conversion, storage, transport, distribution, reconversion, and utilisation [1,5]. Figure 1 shows a typical green H₂ supply chain. Ports and shipping are pivotal nodes within the supply chain. In exporting countries, H₂ is produced via water electrolysis using renewable electricity. The low density of gaseous H₂ necessitates its conversion into alternative forms such as compressed H₂ (CH₂), liquified H₂ (LH₂), or chemical carriers like ammonia, methanol, or liquid organic hydrogen carriers (LOHCs) to facilitate its efficient storage and transportation. After its arrival at the export port, H₂ is shipped to the import port. Hereafter, it undergoes a

distribution phase and, when required, reconversion processes to cater to the needs of end-users, including transportation [6–8], high-temperature industrial applications [9,10], and residential usage [11,12]. At the point of consumption, energy conversion can be achieved through fuel cells, internal combustion engines, steam turbines, gas turbines, and burners.

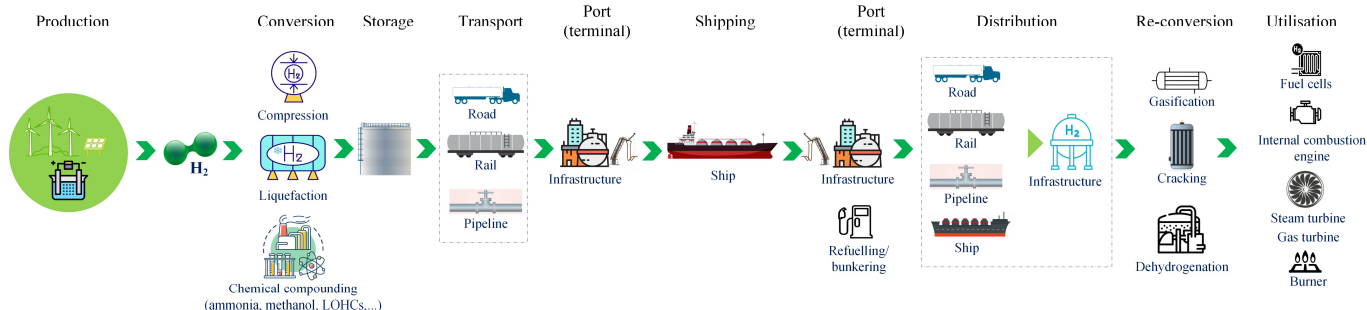


Figure 1. Typical international hydrogen supply chains.

Ports are an important node and link within the supply chain and can be a hub of the H₂ industry from production to consumption. Ports are good locations to produce H₂ if they are close to renewable energy sources; facilitate H₂ transport logistics both for export and import; and utilise H₂ as an energy source for the ports' assets, including vehicles, machinery, and vessels [13–18], that can decarbonise the ports' operations significantly.

This research builds upon significant advancements in green H₂ technology and its applications within port operations and logistics. In recent years, we have seen a surge in pilot projects and strategic initiatives globally, focusing on integrating H₂ into existing energy and industrial systems. For instance, various ports in the world have begun exploring hydrogen-based solutions [1,19,20], from fuel cell technologies for port equipment to large-scale hydrogen production facilities using renewable energy sources. Leading ports like the Port of Hastings in Australia and the Port of Kobe in Japan have initiated hydrogen export and import terminals, setting a precedent for future developments. Furthermore, collaborative efforts between industry stakeholders, government bodies, and research institutions have provided valuable insights into the technical, economic, and regulatory frameworks necessary for establishing robust H₂ supply chains. These pioneering projects and studies form the cornerstone of this research, highlighting the practical and theoretical underpinnings that drive the exploration of hydrogen's potential to transform port operations and development.

Despite ports' significant role in the H₂ supply chain, there is only scanty literature focusing on this area of study. Matthé et al. [21] published a white paper analysing ports' opportunities and challenges in developing H₂ supply chains. An editorial article by Notteboom and Haralambides [22] commented on the critical challenges and opportunities that H₂ can bring to the economics and governance of seaports in Europe. Chen, Fan, Enshaei, Zhang, Shi, Abdussamie, Miwa, Qu, and Yang [1] thoroughly reviewed ports' readiness for the upcoming international H₂ trade. They indicated that ports' readiness for the H₂ international trade is in its infancy. Infrastructure construction or renovation, risk management measures, the establishment of regulations and standards, and education and training all require more effort. Recently, new literature has emerged, exemplified by Deloitte's comprehensive study projecting potential H₂ demand and supply in European ports and coastal areas [23]. This study suggested that up to 42% (22 million tonnes) of the EU's H₂ demand in 2050 could be concentrated in port areas. Fages et al. [24] predicted that green H₂ will decarbonise ports and their neighbouring industries, leading to new port infrastructure (H₂ production, import, and refuelling) in the coming years. Notably, Australia has started reviewing its national H₂ strategy [25], and made advancements in H₂ ports like Bonython, Townsville, and Hedland. Japan has revised its H₂ strategy to focus on building H₂ demand across all economic sectors and importing H₂ from

overseas [26]. These developments underscore ports' vital role in promoting H₂ supply chains. Nevertheless, the existing studies lack firsthand information and data from relevant stakeholders in the port focused on the H₂ supply chain. Hence, this paper fills the gap through an in-depth investigation into ports' opportunities and challenges when integrating H₂ supply chains into their operations. This research took ports in Australia and Japan as research subjects because these countries are at the forefront of the H₂ industry's development globally [1], and international trade of H₂ between Australia and Japan has been demonstrated [27,28]. This research explores how ports in both countries can become logistics centres to best facilitate the H₂ trade and enable the application of H₂ in reducing GHG emissions. The areas of focus cover transport logistics and application functions in the H₂ supply chain, and in this research, the term "H₂ port" is used to refer to a port with these functions. Due to the ongoing demonstration of the H₂ trade between Australia and Japan, this research holds great practical significance. This paper makes the following contributions to H₂ ports.

- Identifying the benefits to ports and their regions by integrating the H₂ supply chain into their operations.
- Determining the infrastructure and facilities required for ports to facilitate H₂ logistics.
- Identifying challenges of H₂ logistics operations in ports.
- Identifying the challenges and barriers associated with adopting H₂ technology in ports.
- Developing a framework for logistics operations and applications of H₂ in ports.
- Providing recommendations to address the current challenges and barriers related to handling H₂ in ports.

This research makes academic contributions to the field of H₂ logistics and port management. First, it provides a comprehensive framework for understanding the integration of H₂ supply chains within port operations, bridging a crucial gap in the existing literature. Second, the study offers empirical data and firsthand insights from stakeholders in Australia and Japan, enhancing the understanding of practical challenges and opportunities in real-world settings. Third, the development of a structured framework for logistics operations and applications of H₂ in ports offers a foundational model that can be adapted and applied in various global contexts. Furthermore, the research identifies and categorises the infrastructural, regulatory, and technological barriers to the adoption of H₂ in ports, providing a detailed analysis that can inform future policy and investment decisions. By addressing both the macro-level strategic implications and the micro-level operational details, this study advances the academic discourse on sustainable port management and green logistics.

Following the introduction, this paper explains the study's methodology. The interview results identify the opportunities, functions, operations, infrastructure, and challenges in both countries in managing H₂ logistics operations and adopting H₂ technologies. Subsequently, this paper, using the survey results, evaluates the readiness levels of H₂ ports. Recommendations are proposed to overcome the existing barriers. Finally, the findings, based on empirical analysis, support the development of a new framework for logistics operations and applications of H₂ in ports. The selected countries for this empirical research are of a certain representativeness, so the findings provide a valuable reference for the development of H₂ ports worldwide.

2. Materials and Methods

This empirical research adopted a mixed-methods methodology. Due to the exploratory nature of H₂ port research, it first employed a qualitative method through semi-structured interviews [29] with key stakeholders of the ports focused on the H₂ supply chain to investigate the opportunities and challenges of H₂ ports in Australia and Japan. Subsequently, a quantitative online survey of port personnel and producers/exporters and importers was conducted to evaluate the readiness levels of H₂ export and import ports in both countries. The interviews and survey involved human information. Therefore,

ethics applications were submitted to the University of Tasmania's Social Sciences Human Research Ethics Committee, which approved them. The interviewees signed consent forms for participation before the interviews were conducted.

This research methodology was designed to address the identified gaps and provide empirical data that enhance the understanding of H₂ supply chains within port operations. The qualitative interviews aimed to capture firsthand insights from stakeholders involved in pioneering projects, thereby aligning with the study's goal of bridging the practical knowledge gap identified in the literature. The quantitative survey complements the qualitative data by providing a structured analysis of the readiness levels of H₂ infrastructure and operations in ports, which is crucial for developing a comprehensive framework, as highlighted in the academic contributions. This mixed-methods approach ensures that the research not only explores theoretical opportunities and challenges but also validates these findings with empirical data from industry practitioners in leading H₂ ports like those in Australia and Japan.

2.1. Interview

The objectives of the interviews were as follows:

- Identify the opportunities for ports and port regions.
- Determine the functions of ports in facilitating the international H₂ trade.
- Explore the requirements for efficient, effective, and safe operations in H₂ ports.
- Evaluate the status of regulations and standards related to H₂ ports.
- Identify potential challenges and barriers to applying H₂ technologies in ports, particularly with regard to logistics.
- Assess the government support required to promote the development of H₂ ports.

An interview guide, as shown in Appendix A, with four sets of questions was developed for four groups of target interviewees, i.e., Group A, port authorities or operators; Group B, H₂ producers, exporters, or importers; Group C, shipping companies; and Group D, governments or their agencies, but some questions were asked to multiple groups. Content analysis methodology was used to analyse and synthesise the interview transcripts based on the following key research words associated with the questions.

- Opportunities: the opportunities of the H₂ trade and its applications for ports and regions;
- Functions: the ports' functions in facilitating the international H₂ trade, including infrastructure and facility requirements;
- Operations: the requirements for efficient, effective, and safe operation in H₂ ports;
- Standards: the status of standards in H₂ operations and applications in ports;
- Challenges: potential challenges of H₂ logistics in ports and barriers to the application of H₂ technologies in ports;
- Supports: support needed from governments.

Considering the nascent nature of this area, the research employed a purposive sampling approach to recruit participants with expertise in the H₂ trade and its application. This research identified ports based on the two countries' H₂ strategies and then determined the potential participants from those ports involved [1]. The participants held key roles within the port focused on the H₂ supply chains, and most of their positions were those of senior managers and above, for example, chief executive officer, chief operating officer, project manager, and chief technical adviser. It is notable that several participants had a chemical and mechanical engineering background (from producers and ports), and some managed or regulated dangerous goods (ports, governments). The demographic information shows the representativeness of the interviewees and the reliability of the data collected.

The interviews were conducted from September 2022 to March 2023. A total of 22 semi-structured interviews were conducted. Table 1 presents the information on the participants and interview methods.

Table 1. The participants' information and interview methods.

Participant No.	Country (State or Region)	Sector	Group	Interview Method
P1	Australia (Tasmania)	Port	A	Face-to-face
P2	Australia (Western Australia)	Port	A	Online
P3	Australia (Victoria)	Port	A	Online
P4	Australia (Queensland)	Port	A	Online
P5	Australia (Tasmania)	Producer/Exporter	B	Online
P6	Australia (Tasmania)	Producer/Exporter	B	Online
P7	Australia (Western Australia)	Producer/Exporter	B	Online
P8	Australia (Western Australia)	Producer/Exporter	B	Online
P9	Australia (Queensland)	Producer/Exporter	B	Online
P10	Australia (Queensland)	Producer/Exporter	B	Online
P11	Australia (Queensland)	Producer	B	Online
P12	Australia (Tasmania)	Government	D	Online
P13	Australia (Western Australia)	Government	D	Online
P14	Japan (Hyōgo Prefecture)	Government	A, D *	Online
P15	Japan (Aichi Prefecture)	Government	A, D *	Online
P16	Japan (Fukushima Prefecture)	Government	A, D *	Online
P17	Japan (Kanagawa Prefecture)	Government	A, D *	Online
P18	Japan (Yamaguchi Prefecture)	Government	A, D *	Online
P19	Japan (Hyōgo Prefecture)	Port/Terminal	A	Online
P20	Japan (Osaka Prefecture)	Importer	B	Online
P21	Japan (Tokyo)	Importer	B	Online
P22	Japan (Tokyo)	Shipping company	C	Online

* Note: in Japan, the port authorities are part of the government; thus, participants 14–18 were assigned to both Groups A and D.

2.2. Online Survey

The online survey was conducted to provide a quantitative understanding of both countries' potential H₂ forms for trade and utilisation, the status of the ports' infrastructure and facilities, as well as critical factors for efficient and effective H₂ ports. A closed-ended structured questionnaire was developed based on the interview outcomes and made available to potential participants through online access with Microsoft Forms software (version: 2022). The questionnaire includes the following sections with relevant questions:

- Section A: Demographics.
- Section B: Questions about H₂ forms for trade and utilisations.
- Section C: Infrastructure sufficiency for H₂ ports.
- Section D: Berth utilisations.
- Section E: Readiness levels of critical factors for an efficient and effective H₂ port.

The survey employed a nine-point Likert scale to gauge participants' opinions on the infrastructure sufficiency levels, with 1 = Non-existent, 3 = Inadequate, 5 = Acceptable, 7 = Adequate, and 9 = Satisfactory, and readiness levels of critical factors, with 1 = Idea, 3 = Actionable plan, 5 = Development, 7 = Validation/Demonstration, and 9 = Ready for implementation. The numbers between the above-mentioned numbers represent intermediate states. The sufficiency levels of infrastructure and the readiness levels of critical factors defined in this paper were inspired by the Technology Readiness Levels (TRLs) framework defined in the ISO 16290 standard [30], which is widely utilised in the industry. When analysing the results, the arithmetic mean of the collected data is used to represent the results.

The criterion for selecting participants was set to their having H₂-related knowledge or experience. A purposive sampling approach was, therefore, applied to obtain representative samples. This research invited those potential participants involved in H₂ hub projects announced by the governments [1]. The research team distributed the online survey questionnaire to 44 potential participants, i.e., port personnel, producers/exporters, and importers (Australia, 34 and Japan, 10) through emails and LinkedIn. The online survey was conducted from March to May 2023.

3. Interview Results

This section reveals the opportunities and challenges of H₂ ports. The analysis results presented in the below subsections are based on the research keywords in Section 2.1.

3.1. Opportunities

Questions (1) and (2) in Appendix A relating to H₂ forms, potential markets, and opportunities for ports and their regions were posed to participants in groups A, B, and D. The responses to these questions are summarised below.

3.1.1. Hydrogen Forms and Potential Markets

Figure 2 shows that fifteen participants (eleven from Australia and four from Japan) indicated the H₂ forms they would focus on, and the potential markets provided by participants in Group B.

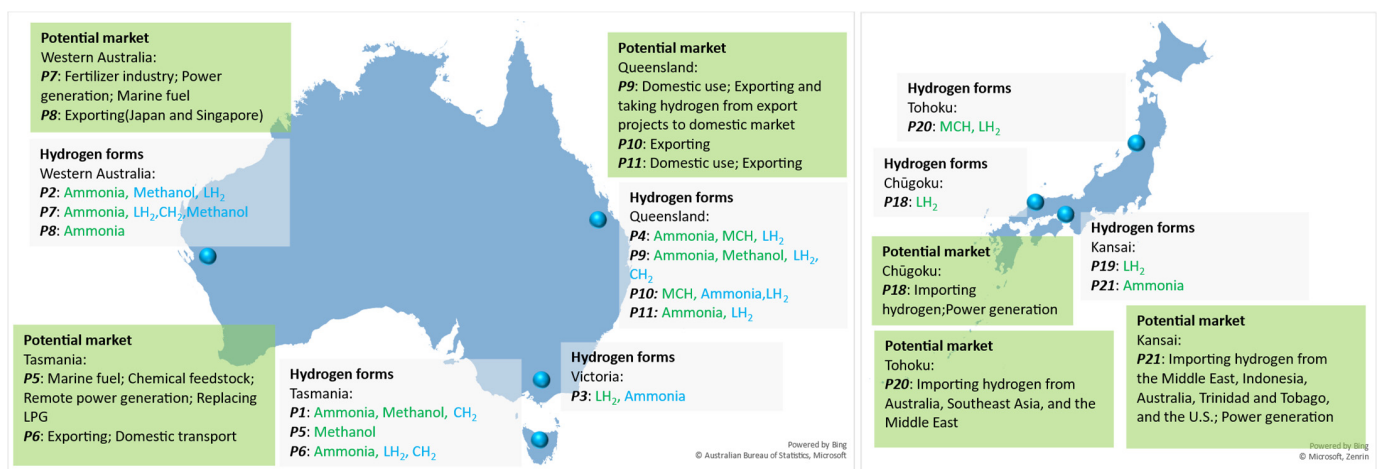


Figure 2. Hydrogen forms and potential markets. Note: green font indicates the near-term focus, while blue font indicates the long-term focus.

In Australia, ammonia is the primary focus in the near term, followed by methanol and methylcyclohexane (MCH), a type of LOHC [31]. However, the participant from Victoria prioritised cryogenic LH₂ due to the ongoing HySTRA pilot project being conducted with Japan [32]. Regarding the potential market, all participants anticipated that Australia will be a major H₂ (or its derivatives) exporter. The participants also highlighted domestic usage options. Japan will be the major H₂ importer, focusing on MCH, LH₂, and ammonia, under its national H₂ strategy [33], with a potential expansion into power generation using H₂.

3.1.2. Opportunities for Ports and Regions

Twelve participants in groups A and D provided insights into the opportunities of integrating H₂ into the economy. Table 2 summarises the responses. From the port perspective, the participants from Australian ports believed that the opportunity lay mainly in exports. It is worth mentioning that P2 pointed out the need to import renewable energy infrastructure prior to producing H₂. The Japanese ports focused on strengthening the functionality of importing H₂ and cultivating public awareness of a H₂ society. All the participants from ports viewed H₂ as an opportunity for decarbonisation. From the government perspective, Australia aims for H₂ export leadership and decarbonisation of hard-to-abate sectors, like transportation and steel manufacturing, while Japan seeks to become a H₂ society, benefiting port cities.

Table 2. Information on ports and their regions' opportunities in the H₂ economy.

Port	Region
<ul style="list-style-type: none"> • Becoming a major exporter of renewable fuels. • Becoming a renewable energy infrastructure importer. • Growing regional ports (most of the renewable energy projects are in regional areas). • Providing a backbone for producers. • Adding volume to ports' trade. • Decarbonising ports' activities. 	<ul style="list-style-type: none"> • Becoming a H₂ export leader. • Decarbonising the hard-to-abate industries such as transport, agriculture, mining, and metallurgy. • Providing alternative fuels for business transition processes. • Boosting H₂ technology development.
<ul style="list-style-type: none"> • Enhancing the functions of the ports. • Fostering public awareness of the H₂ society. • Becoming carbon-neutral ports. • Decarbonising the heavy industry near the port to revitalise the industry. 	<ul style="list-style-type: none"> • Becoming a H₂ society leader. • Benefiting the businesses of the port city. • Decarbonising power plants in the port areas.

3.2. Functions

Three function-related questions (Q3–5) in the Appendix A were posed to the participants in groups A, B, and C. The responses to these questions are summarised below.

3.2.1. Potential Hydrogen Exporting/Importing Ports

Combining groups A and B participants' responses and the published literature review outcome [1], Figure 3 presents sixteen potential H₂ ports in Australia and Japan. Out of them, ten ports are in Australia (Hedland, Dampier, Fremantle, Bonython, Geelong, Hastings, Bell Bay, Newcastle, Gladstone, and Townsville), and six are in Japan (Tokuyama, Kudamatsu, Kobe, Nagoya, Yokohama, Onahama, and Niigata). The Australian ports serve as exporting ports, whereas Japan's ports function as importing ports.

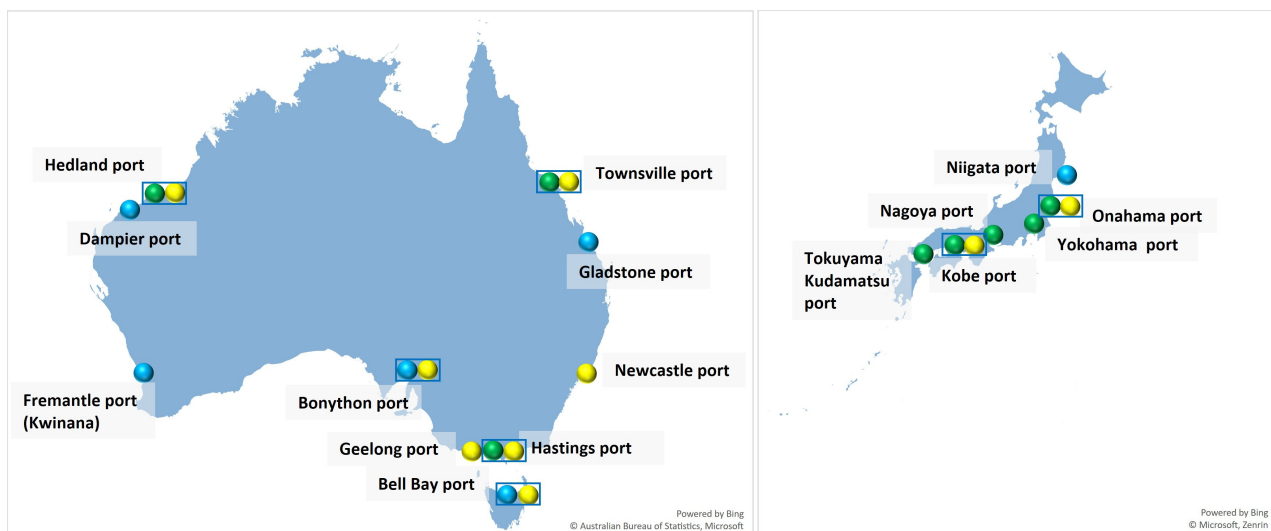


Figure 3. Identified potential Hydrogen Ports. Note: yellow dots represent the ports identified by literature review [1]; blue dots represent the ports identified by Participant Group B; green dots represent the ports described by Participant Group A.

3.2.2. Port Infrastructure and Facilities

New port infrastructure and facilities are required to support the trade of H₂ and its derivatives, and the existing infrastructure needs to be retrofitted to accommodate them. The required infrastructure and facilities for ports are summarised below:

- Process plants, for instance, liquification plants, regasification plants, hydrogenation plants, and dehydrogenation plants (P1, P2, P3, P4, P5, P6, P7, P9, P10, P11);
- Storage tanks (P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, P11, P14, P20, P21, P22);
- Pipelines (P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, P11, P15, P17, P18, P19);
- Berths (P1, P2, P3, P4, P5, P6, P7, P8, P10, P11, P16, P19);
- Loading/unloading equipment (P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, P11, P15, P17, P21, P22);
- Powerlines (P1, P2, P5, P6, P7);
- Roads (P1, P6);
- Refuelling stations (P1, P4, P5, P9, P11, P19);
- Bunkering vessels (P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, P17, P19, P21);
- Security systems (P1, P7, P8);
- Safety systems (P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, P11, P14, P15, P16, P17, P18, P19, P20, P21, P22).

3.2.3. Ships

Only P22 from a Japanese shipping company was available to provide insights on H₂ shipping, as the industry is still in the early stages of development, and the shipping company is among the very few pioneers in the world who possess relevant insights in the field. Nevertheless, several participants from ports or producers, such as P1, P3, P8, P10, and P20, also shared their perspectives indirectly, which increases the credibility of the findings.

Participants mentioned that the current chemical tanker fleet could transport ammonia, methanol, and MCH, but new ship designs are needed for LH₂ and CH₂ shipping. Although the world's first LH₂ carrier was tested in the HySTRA project, building LH₂ ships still poses several challenges, such as building cryogenic tanks and managing boil-off gas. On the other hand, CH₂ ships could only be utilised for short routes due to their low shipping efficiency. Regarding investing in a new shipping fleet, P22's company was exploring the possibility of building vessels. International Organization for Standardization (ISO) tank containers are an initial solution for shipping H₂ and its derivatives.

3.3. Operations

The researchers asked participants from groups A, B, and C about the operational risks. Specifically, participants from groups A and C were asked about their training needs. The following two subsections describe the findings.

3.3.1. Hydrogen-Related Operational Risks

Establishing a comprehensive risk management system from scratch is crucial for ports handling H₂ as a new commodity. Some participants believed that the risks associated with ammonia, methanol, and MCH (toluene-like) were manageable because they had been transported as chemical goods in ports for decades. However, most participants acknowledged that, as larger-scale energy commodities, there was a lack of accumulated experience in risk management for these goods. Table 3 summarises the associated operational risks of H₂ and its derivatives based on the participants' views, including the causes of risks, effects, and potential consequences.

Table 3. Operational risks in ports.

Cause	Effect	Potential Consequence
Insufficient risk assessment, particularly lacking a standardised methodology	<ul style="list-style-type: none"> • Inadequate risk mitigation measures (safety zone, firefighting capacity, blast wall, etc.) 	<ul style="list-style-type: none"> • Life loss • Asset loss
Insufficient safety prevention	<ul style="list-style-type: none"> • Gas detection failure • Shutdown system failure 	<ul style="list-style-type: none"> • Leak/spill deterioration

Table 3. Cont.

Cause	Effect	Potential Consequence
Inadequate emergency response	<ul style="list-style-type: none"> • Unavailable firefighting • Insufficient medical rescue resources 	<ul style="list-style-type: none"> • Life loss • Asset loss
Inadequate cargo/passenger operation protocol	<ul style="list-style-type: none"> • Improper concurrent operations 	<ul style="list-style-type: none"> • Loss of containment • Potential chemical reactions
Inadequate security protocol	<ul style="list-style-type: none"> • Sabotage • Accidental mishap 	<ul style="list-style-type: none"> • Loss of containment
Leak/spill	<ul style="list-style-type: none"> • Fire and explosion (H₂, ammonia) • Toxicity (ammonia, methanol, MCH) • Cryogenic damage (LH₂) 	<ul style="list-style-type: none"> • Large exclusion zone • Human life or marine life loss • Marine environmental damage

3.3.2. Training and Education

A significant training and education gap exists. According to participants, although some basic H₂-related training programs are available, there is a shortage of experienced personnel to offer training for real-world operations.

3.4. Standards

All four groups of participants responded to the question regarding standards. The interviewees highlighted that the standards for safety and environmental aspects were already in place for ammonia and methanol, and the existing toluene-relevant standards could be referred to for MCH. Some international standards are already available for the H₂ industry, such as ISO and International Electrotechnical Commission (IEC) standards. However, most existing standards are primarily suitable for industrial use and not for using H₂ and its derivatives as energy sources. Consequently, there is still a significant gap in standards.

A total of 21 participants provided their expectations in terms of standards. Sixteen (76%) participants preferred international standards, while three (14%) favoured local standards, and two participants (10%) indicated that their preference is dependent on shipping routes and ports.

Governments can accelerate standardisation, and some have taken action. As stated by P1 and P4, the Australian Standards Committee was examining H₂ standardisation; the Australian government's H₂ regulation is in progress [34]. Additionally, P15 and P17 highlighted that the Japanese government and enterprises were actively involved in developing ISO standards, particularly for LH₂.

3.5. Challenges

Six questions (Q9–14) were asked to groups A, B, C and D. The analysis results reveal four aspects of challenges, i.e., port development, H₂ application, H₂ refuelling and bunkering, and shipping.

3.5.1. Port Development

Sixteen out of twenty-two participants expressed their concerns regarding this aspect, and five challenges were identified. The first major challenge to the development of H₂ ports is land use. Six participants (P1, P2, P4, P5, P12, and P13) highlighted that the availability of land space is a significant obstacle. Large land space is needed for H₂ production, in-port infrastructure building or upgrading, and port safety zone layout upgrading.

The second major challenge lies in the uncertainty of H₂ demand, which is the primary concern for participants from the Japanese importing ports (P14, P15, P16, and P17). While there were optimistic predictions about future H₂ demand, ports hesitate to invest without secure selling agreements.

The third major challenge is the lack of infrastructure. Building new infrastructure is necessary to handle H₂, and even the existing infrastructure for alternative H₂ forms needs to be scaled up for upcoming larger-scale trade. However, building large H₂ infrastructure, especially LH₂ tanks, faces technological limitations, as mentioned by P2. Additionally, there is a gap in the standardisation of infrastructure construction. With the entry of small H₂ producers and exporters into the market, P2 suggested that common-use infrastructure should be considered. However, P7 raised concerns about the difficulty of certifying the carbon intensity of the cargo from different producers in the common-use tanks. Furthermore, P3 raised the question of repurposing the retiring oil and gas infrastructure for H₂ and its derivatives.

The fourth major challenge is insufficient education. P16 emphasised that providing education on advancements in H₂ technologies could increase investors' confidence in the development of ports.

The fifth major challenge is to obtain social licence for H₂ ports. As some ports are situated in densely populated areas, more extensive risk and environmental assessments must be conducted and publicised to build public confidence.

3.5.2. Hydrogen Applications in Ports

Four participants from Group A provided their views on using H₂ in ports. P3 and P4 expressed their commitment to powering the ports with renewable energy but were undecided between batteries and H₂.

3.5.3. Hydrogen Refuelling and Bunkering

Providing H₂ fuel services could be an opportunity for ports [35–38]. Participants P1, P3, and P4 from Australian ports stated that they were exploring the possibility of building H₂ refuelling stations within their ports. Regarding maritime bunkering, P2 stated that their port was considering ammonia bunkering services. The other interviewees, P3 and P4, stated that once the shipping industry locked down on the future fuel types, they would consider bunkering up vessels accordingly.

In summary, port challenges with H₂ refuelling and bunkering result from uncertainty in the downstream H₂ application market. The availability of infrastructure is crucial to stimulate downstream growth, creating a “chicken and egg” dilemma.

3.5.4. Shipping

In terms of H₂ transportation, existing tankers can be used for ammonia or MCH. Ammonia transport is expected to shift from midsize gas tankers to very large tankers. However, the existing ammonia-receiving ports are not large enough to accommodate large vessels, so it is necessary to renovate berths. When it comes to CH₂ or LH₂, technical demonstrations in ports are required. As for using H₂ or its derivatives as a maritime fuel, ammonia engines are expected to appear around 2025, which could make ammonia-fuelled ships an attractive option due to their high energy density and zero carbon emissions. In some green corridors, cape-size bulk carriers, car carriers, and ammonia carriers are potential users of ammonia fuel. Therefore, establishing fuel bunkering facilities or barges poses a challenge for ports.

3.6. Government Support

The participants expected different kinds of support for developing H₂ ports. This section presents the analysis results regarding government support.

3.6.1. Australia

Interview results revealed that several key supports could be considered. Firstly, policies and regulations are necessary for H₂ production, green certifications, and operational procedures. P1, P2, and P3 all highlighted this aspect. Secondly, financial support is crucial. Both direct and indirect funding options should be explored. P1 suggested that the funding

should be directed towards infrastructure development. Indirect financial support could be provided in the form of levies or carbon taxes imposed on the disposal of fossil fuels, as suggested by P5, P7, and P8. Thirdly, a constant review of published H₂ strategies is necessary, as suggested by P4. Fourthly, government departments (electricity, water resources, renewable energy, and infrastructure) should work together to promote efficient port development. Finally, Australia should play an essential role in inter-government organisations to support the development of a seamless H₂ supply chain.

3.6.2. Japan

The Japanese government has established several initiatives and funds to promote the development of H₂ ports, including the Carbon Neutral Port Initiative, the New Energy and Industrial Technology Development Organization, the METI (Ministry of Economy, Trade and Industry) Green Transformation League project, and the METI Green Innovation Fund project. Despite these government efforts, some participants felt that more support was necessary. As P18 mentioned, the government should establish a rating and certification system for ports implementing carbon reduction measures.

4. Survey Results

The survey results are presented in the following subsections, covering H₂ trading forms, infrastructure sufficiency, H₂ utilisation, berth utilisation, and readiness levels of critical factors for H₂ ports.

4.1. Demographics

A total of 20 responses were received (13 from Australia and 7 from Japan, as shown in Figure 4), representing a response rate of 45%. Figure 4 also shows the distribution of participants from different sectors. Figure 5 presents the professional role and service time distribution of the participants, showing the representativeness of participants' expertise and knowledge in the research area. Most of the participants were in managerial positions or above. It is notable that four participants were engineering specialists in the research area, i.e., lead engineer, chief technical officer, technical lead, and hydrogen development specialist. Regarding work experience, 68% of the participants had more than 10 years of professional experience.

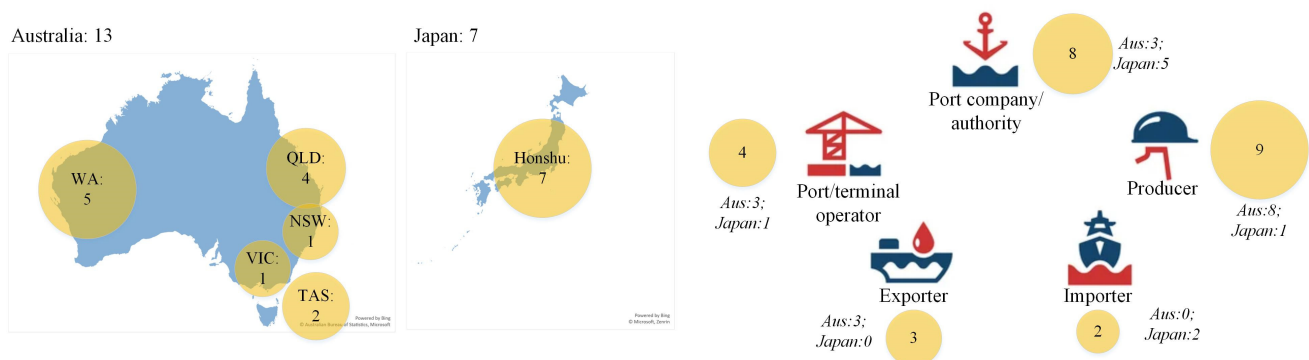


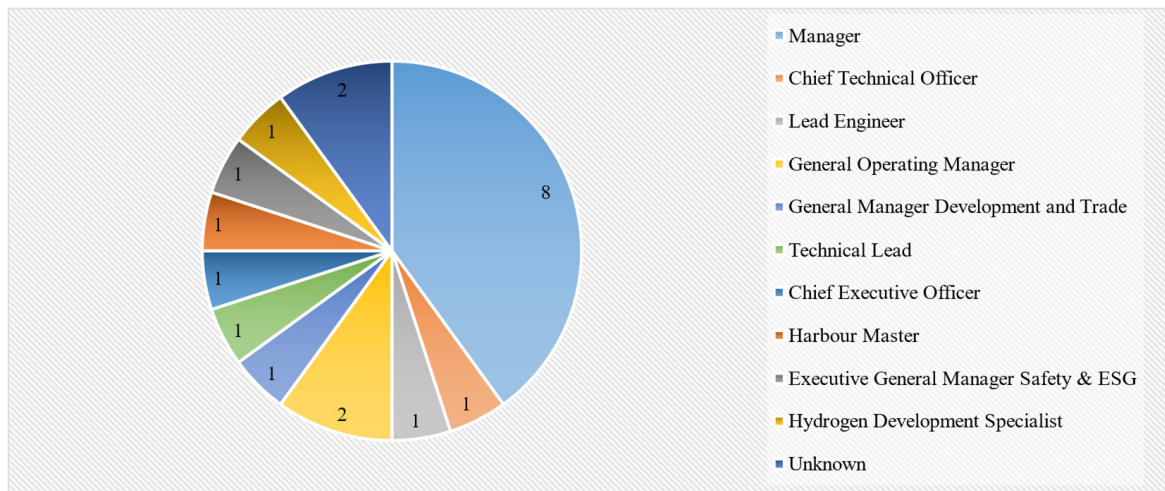
Figure 4. Distribution of the participants. Note: some participants indicated multiple fields.

4.2. Hydrogen Forms for Trade and Utilisation

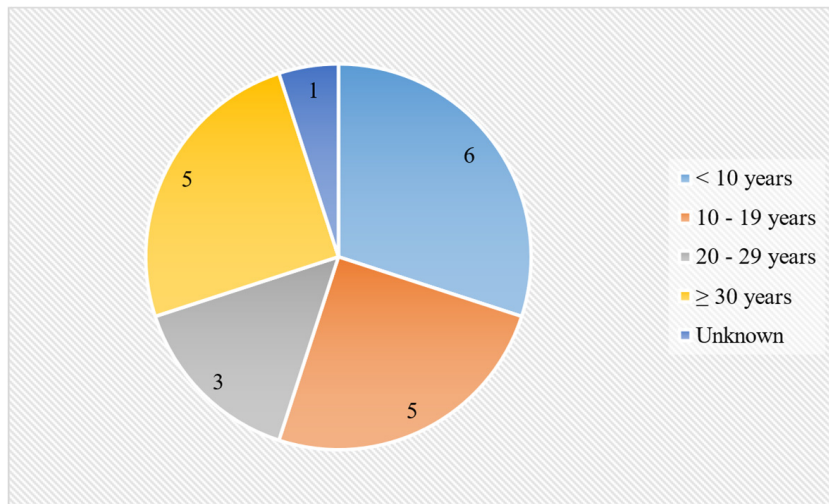
Different H₂ forms, including CH₂ and LH₂, and H₂ derivatives, such as ammonia, methanol, and LOHCs, were considered for trade.

4.2.1. Hydrogen Forms for International Trade

Figure 6 depicts the distribution of H₂ forms that participants planned to produce, export, or import. Ammonia exhibits the highest counts, followed by LH₂, LOHCs, CH₂, and methanol, in decreasing order.



(a) Professional roles



(b) Service years

Figure 5. Participants’ professional roles and service years. (a) Eighteen participants indicated their roles. (b) Nineteen participants indicated their service years.

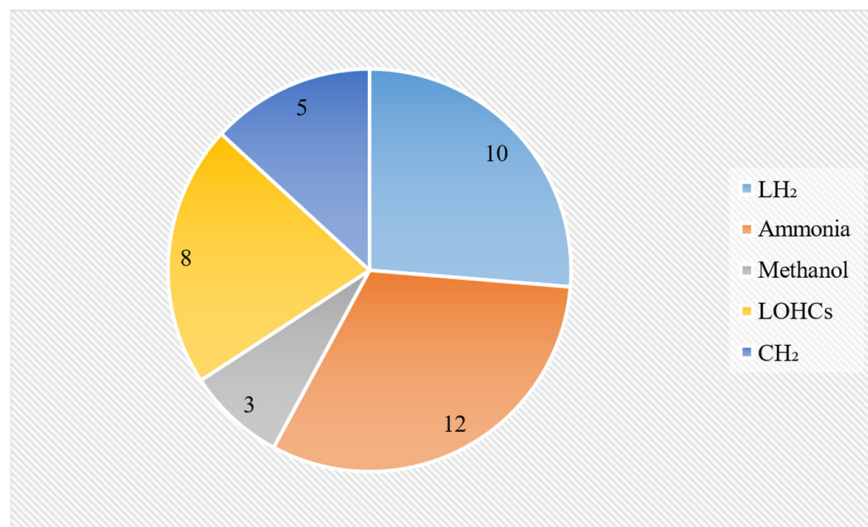


Figure 6. Distribution of hydrogen forms for production, exporting, or importing.

4.2.2. Hydrogen Utilisation in Ports

In terms of the intention to utilise H_2 or its derivatives, no participants provided negative responses. Figure 7 shows the distribution of ports' assets that have the potential to be decarbonised using H_2 or its derivatives. Forklifts received the highest counts (11), followed by yard trucks (6), container movers/reach stackers (5), tugboats (5), harbour crafts (5), pilot boats (4), bunker barges (4), prime movers (3), gantry cranes (1), and dozers (1).

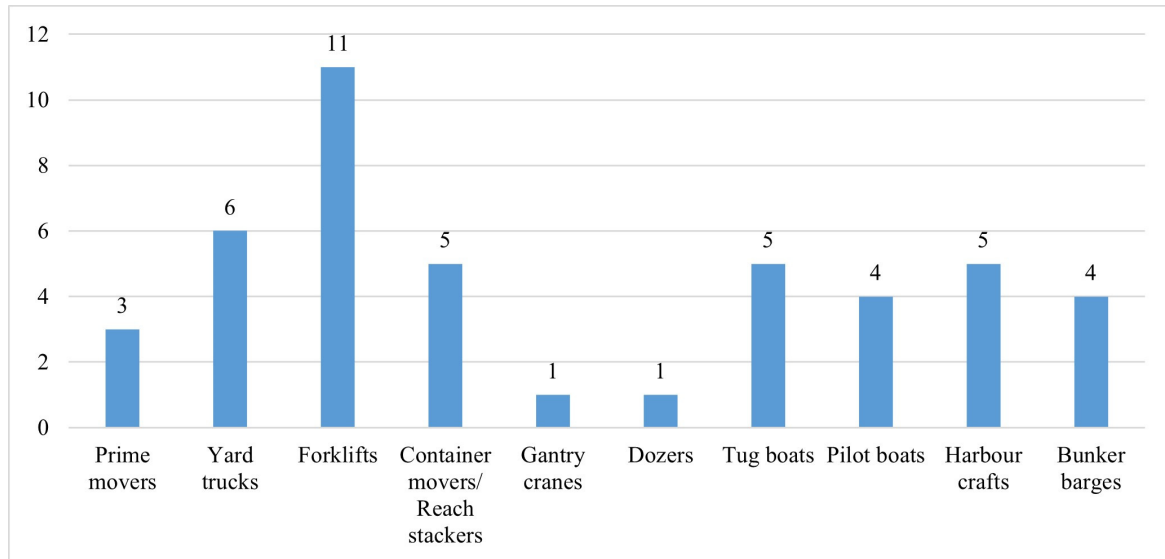


Figure 7. Distribution of ports' assets that will be decarbonised using hydrogen or its derivatives.

Figure 8 displays the participants' intention to provide H_2 or H_2 -based refuelling or bunkering services. Seventeen respondents will or may provide them, and only one participant provided a "no" response. The distribution of fuel types shows that eleven participants expressed a preference for providing ammonia as the primary fuel, followed by methanol, CH_2 , and LH_2 .

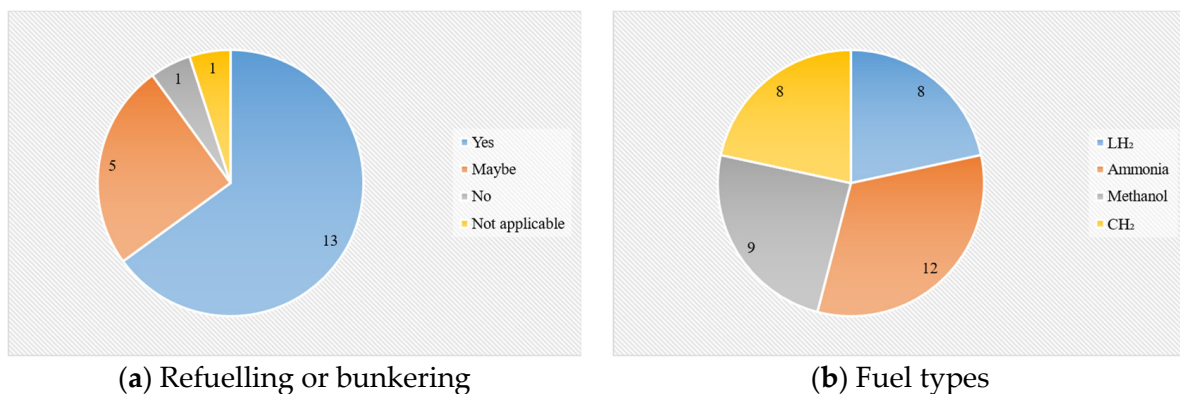


Figure 8. Participants' intention to provide refuelling or bunkering services, and the distribution of fuel types.

4.3. Infrastructure Requirement and Sufficiency for Hydrogen Ports

Participants were asked to indicate the requirements and sufficiency levels of port infrastructure and facilities for managing the different H_2 forms. Figure 9 shows that participants considered safety equipment and monitoring and control systems (19 counts for both) to be the most required infrastructure and facilities, followed by storage tanks (18), loading/unloading facilities (17), berths (14), liquefaction facilities (14), pipelines (cryogenic temperature) (13), and pipelines (normal temperature) (12). The least required

port infrastructure and facilities were refuelling stations. Additionally, two Australian participants provided comments in their responses suggesting that bunkering barges are required infrastructure. Figure 10 further presents their corresponding sufficiency levels in Australia and Japan, respectively. The sufficiency levels for all port infrastructure and facilities were below or equal to 5, below the acceptable range.

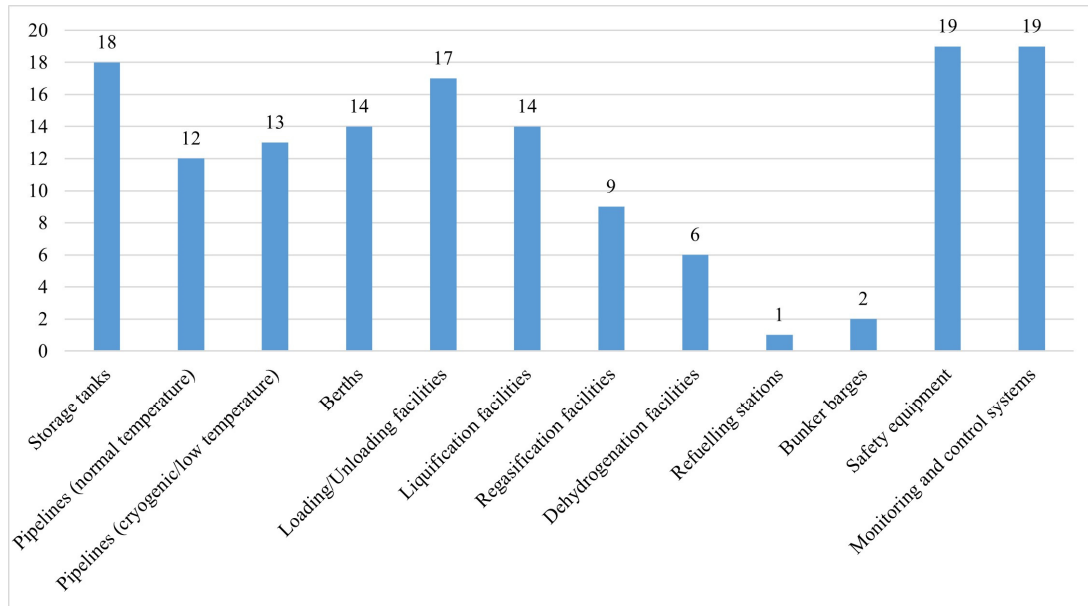


Figure 9. Response count for each infrastructure or facility.

No.	Infrastructure or facility	Response count	Sufficiency Level											
			1	2	3	4	5	6	7	8	9			
			Non-existent		Inadequate		Acceptable		Adequate		Satisfactory			
1	Storage tanks	12			2.85	▼								
2	Pipelines (normal temperature)	8			2.54	▼								
3	Pipelines (cryogenic/low temperature)	9			2.1	▼								
4	Berths	10												
5	Loading/Unloading facilities	12			2.77	▼								
6	Liquification facilities	8		1.89	▼									
7	Regasification facilities	4			1.33	▼								
8	Dehydrogenation facilities	1												
9	Safety equipment	12												
10	Monitoring and control systems	12												
11	Truck refuelling stations	0												
12	Bunkering barges	2												

(a) Australia

No.	Infrastructure or facility	Response count	Sufficiency Level											
			1	2	3	4	5	6	7	8	9			
			Non-existent		Inadequate		Acceptable		Adequate		Satisfactory			
1	Storage tanks	6			2.83	▼								
2	Pipelines (normal temperature)	4												
3	Pipelines (cryogenic/low temperature)	5			2.4	▼								
4	Berths	4												
5	Loading/Unloading facilities	7												
6	Liquification facilities	6												
7	Regasification facilities	5												
8	Dehydrogenation facilities	3												
9	Safety equipment	6												
10	Monitoring and control systems	6												
11	Truck refuelling stations	1												
12	Bunkering barges	0												

(b) Japan

Figure 10. Response counts for each infrastructure or facility.

4.4. Berth Utilisation

From the port operation and management perspective, common-use berths offer flexibility and cost efficiency. However, they may lack customisation. Dedicated berths provide tailored infrastructure for customers but may have higher costs and the potential for under-utilisation. Figure 11 presents the participants’ berth use preferences. Most participants (14) expressed a preference for using dedicated berths. On the other hand, six participants preferred common-use berths. This is because a bulk liquid berth with multiple loading arms can cater to a range of H₂ derivatives, according to the participants’ comments.

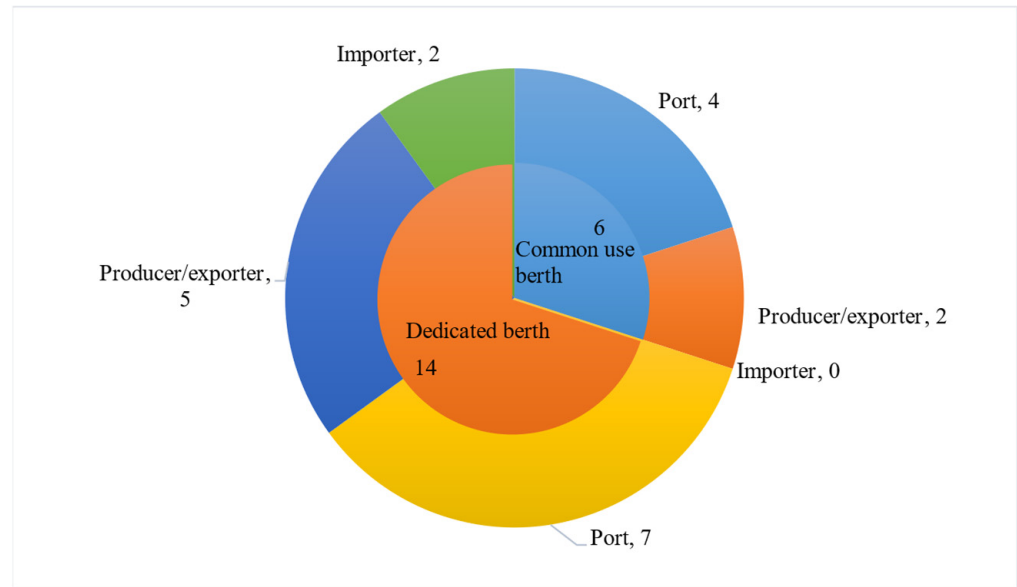


Figure 11. Participants’ preferences for common-use and dedicated berths.

4.5. Readiness Levels of Critical Factors for Efficient and Effective Hydrogen Ports

Five critical factors for efficient and effective H₂ ports were identified, namely, regulations and standards, infrastructure, safety measures, personnel training, and government support, based on the interview results. Participants were asked to assess the readiness levels for these factors. As shown in Figure 12, in Australia, the readiness levels of three factors, infrastructure, personnel training, and government supports, were below 5; two factors, regulations and standards and safety measures, were slightly above 5. In Japan, all factors were below 5. The results indicate that the critical factors for efficient and effective H₂ ports in both countries were in the development stage or below.

No.	Critical factors	Response count	Readiness Level								
			1	2	3	4	5	6	7	8	9
			Idea		Actionable plan		Development		Validation/ Demonstration		Ready for implementation
1	Regulations and standards	13					5.15				
2	Infrastructure	13				4					
3	Safety measures	13						5.15			
4	Personnel training	13				3.07					
5	Government supports	13				3.07					

(a) Australia

Figure 12. Cont.

No.	Critical factors	Response count	Readiness Level								
			1	2	3	4	5	6	7	8	9
			Idea		Actionable plan		Development		Validation/ Demonstration		Ready for implementation
1	Regulations and standards	7			3.86	▼					
2	Infrastructure	7		▼	3						
3	Safety measures	7				▼	4.42				
4	Personnel training	7			3.86	▼					
5	Government supports	7				▼					

(b) Japan

Figure 12. Readiness levels of critical factors for efficient and effective hydrogen ports.

5. Discussion and Recommendations

This empirical research identified opportunities for ports' involvement in the H₂ economy in Australia and Japan. However, there are significant challenges and barriers to both countries' ports' readiness to integrate the H₂ supply chain. These include insufficient infrastructure, lack of regulations and standards, insufficient understanding of H₂ safety, lack of practical personnel training, and obtaining social licence. This section discusses potential solutions to the challenges of expediting the development of H₂ ports.

5.1. Accelerating Port Infrastructure Development

The infrastructure and facilities required for H₂ ports are still in an early stage of development. For improving the readiness of infrastructure and facilities, the following strategies are recommended:

- All parties should work together, share information, and establish a collective understanding of the prospects of the H₂ supply chain. This can inspire investors' confidence and facilitate the expedited development of infrastructure.
- Technological advancements are needed to address the challenges associated with the large-scale storage and handling of H₂ and its derivatives. For example, scaling up LH₂ storage and handling in ports requires technological breakthroughs.
- The current level of financial support for developing H₂ ports' infrastructure needs to be increased. Solutions could be among the following:
 - Increase financial support from governments to attract investment and alleviate the financial burden on port operators.
 - Public-private partnerships should be encouraged to leverage private sector investments and expertise.

5.2. Increasing Incentives for Ports to Support Decarbonisation

There are barriers to H₂ applications in ports, such as the lack of regulatory support and investment. The incentive mechanism is essential [39,40]. To enhance ports' role in utilising H₂, governments could consider providing the following incentives:

- Providing direct financial incentives to ports for investing in H₂ powering assets.
- Implementing tax reductions for ports that contribute significantly to reducing GHG emissions.
- Establishing an incentive mechanism to stimulate the creation of domestic H₂ demand markets, increasing the certainty of H₂ demand in or near ports.

5.3. Adopting a Stakeholder Collaboration Approach for Establishing Regulations and Standards

There is a lack of port-specific regulations and standards. To address these challenges, collaboration between stakeholders is critical, and strategies are suggested below:

- Governments and regulatory bodies (international or national) should collaborate to establish port-specific regulations and standards for infrastructure, safety, and

environmental aspects. For example, the International Maritime Organization (IMO), in addition to working on regulations for H₂ shipping, can consider regulating H₂ ports to provide guidance for member states [41].

- Industry stakeholders should actively participate in developing regulations and standards to ensure they are practical and effective.
- Knowledge sharing and collaboration among countries should be promoted to harmonise regulations and facilitate international trade in H₂.

5.4. Enhancing Understanding of H₂ Safety

Due to hydrogen's safety characteristics, its operation and use at ports differ greatly from traditional fuels [42]. Hence, it is important to do the following:

- Develop training programs and initiatives to enhance the understanding of H₂ safety risks among port personnel and relevant stakeholders.
- Share experience and collaborate with industries with expertise in handling hazardous materials that can help develop robust safety protocols. Knowledge gained from the aerospace and LNG industries can be valuable. In the aerospace industry, the US National Aeronautics and Space Administration (NASA) H₂ safety standards can serve as a significant reference [43]. In the LNG industry, the well-developed regulatory framework for LNG ships developed by the IMO and the comprehensive standards system established by the Society of International Gas Tanker and Terminal Operators (SIGTTO) over 60 years, covering port facilities, cargo operations, and ships [44], can provide a reference for the safe construction and operations of H₂ ports and shipping.

5.5. Developing Practical Training

There are currently some theoretical training programs available in the H₂ industry [45–47]. However, there is a noticeable lack of practical training. To address this challenge, this research recommends the following solutions:

- Building a H₂ knowledge-sharing platform based on the existing global port cooperation organisations (e.g., the International Association of Ports and Harbors, IAPH).
- Forming partnerships between academic institutions, industry experts, and port authorities to provide comprehensive and hands-on training opportunities.

5.6. Promoting Public Awareness to Facilitate Obtaining Social Licence

At present, the public's comprehensive understanding of the social, economic, and environmental impacts of H₂ ports is still limited [1]. To facilitate obtaining social licence, it is essential to do the following:

- Conduct public education campaigns via websites, forums, outreach programs, and workshops to raise awareness and address misconceptions.
- Foster partnerships with local communities, non-governmental organisations, and academic institutions to conduct independent studies, providing unbiased information.
- Engage local communities through dialogues, consultations, and regular updates to encourage participation and address concerns in project planning and decision-making.

6. Operational Framework for a H₂ Port

To establish a clear operational process for a H₂ port, this paper proposes an operational framework based on the findings, as shown in Figure 13. The framework encompasses essential elements, user-oriented working processes, and government support.

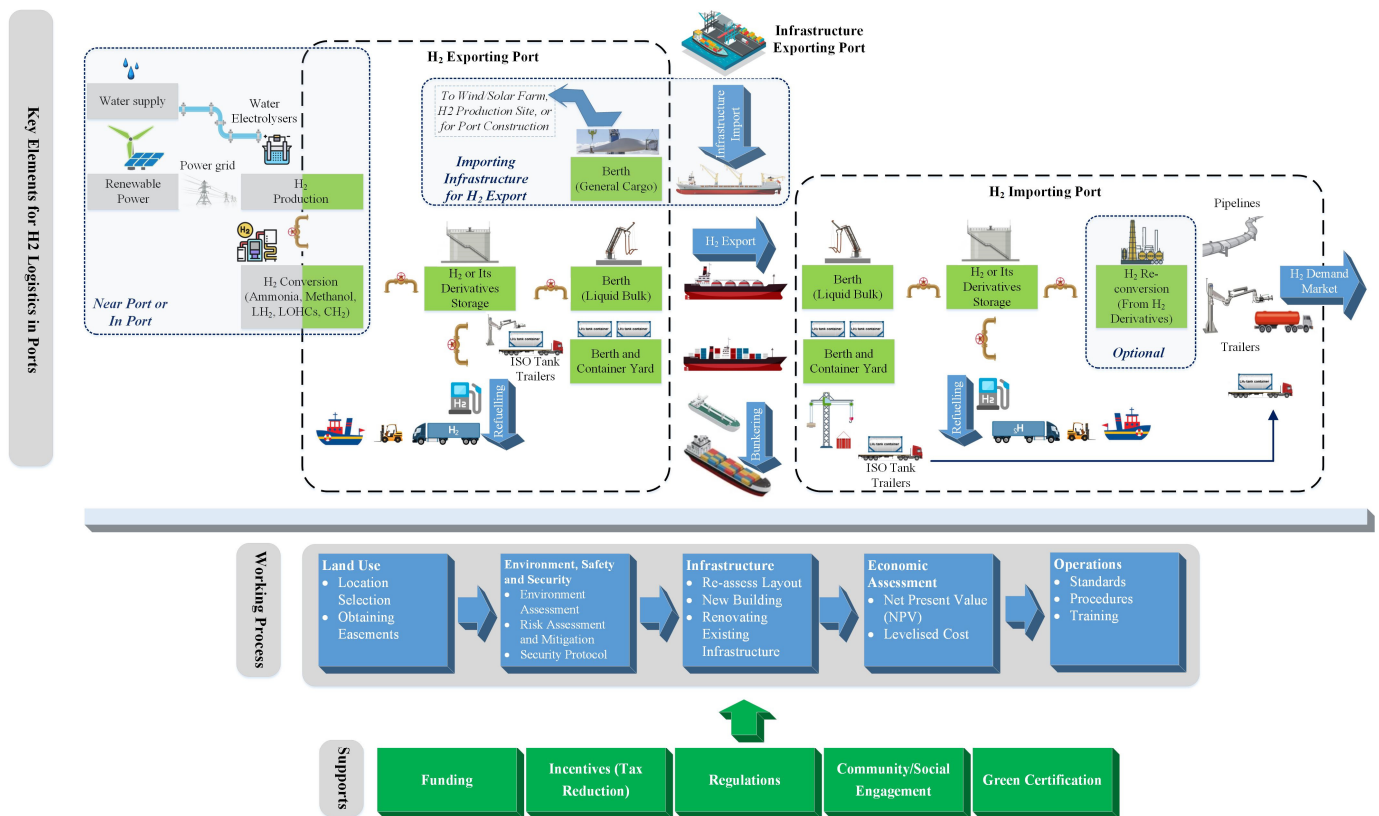


Figure 13. Framework for logistical operations involving H₂ and application of H₂ technology in ports.

6.1. Essential Elements

The framework focuses on H₂ exporting and importing ports. On the export side, a port's initial task is to transition its role to import the necessary infrastructural elements for H₂ production. The shift in functions and roles may differ from the traditional role of many ports. Consequently, new general cargo berths and additional facilities might be required.

The sites for H₂ production and conversion can be situated near or within ports. Pipelines are essential for the transportation of H₂ and its derivatives. Storage tanks play a vital role in the infrastructure. It is also necessary to construct or retrofit common-use or dedicated liquid bulk berths. If ISO tanks are utilised, tank-container berths and stock yards become necessary.

An importing port is equipped with liquid bulk berths and/or container berths and yards. The liquid bulk commodity is stored in tanks and, if needed, reconverted into pure H₂, which is transported to the market through pipelines, road tankers, or ISO tank trailers.

To facilitate the use of H₂ within ports, the establishment of refuelling stations becomes necessary. Moreover, to supply H₂-based fuel to large vessels, the presence of bunkering infrastructure is essential.

6.2. Working Process

The proposed working process consists of five steps, explained in detail below.

Step 1 is to acquire sufficient land for renewable power generation, power grid access, water supplies, H₂ production, and H₂ conversions.

Step 2 involves evaluating the environmental, safety, and security aspects. Most of the H₂ derivatives are toxic. Therefore, it is crucial to conduct a thorough assessment of their potential effects on the environment. All forms of H₂ pose fire and explosion risks, making it necessary to perform safety risk assessments. In addition, existing security protocols at ports should be reviewed and potentially revised.

Step 3 focuses on the construction or renovation of port infrastructure. To begin, the port layout should be thoroughly reassessed from a safety perspective. Additionally, existing port facilities may need to be renovated or upgraded to meet the specific requirements for handling H₂ and its derivatives.

Step 4 involves conducting economic assessments and plays a pivotal role in determining the pricing of H₂. It is crucial to consider the costs associated with port facilities, including both capital expenditures and operational expenditures. Moreover, obtaining the levelised port cost of H₂ provides valuable insights into the overall cost dynamics.

Step 5 focuses on the efficient and effective operation of a H₂ port. To achieve this, it is imperative to adhere to international/local standards and port operation procedures. Additionally, providing training to relevant personnel is crucial to minimise human errors.

6.3. Government Support

To achieve the transformation of ports into H₂ ports, comprehensive support from governments is necessary. The needed support includes funding, incentives, regulations, community/social engagement, and green certification.

7. Conclusions

On a global scale, the H₂ supply chain is rapidly developing, and H₂ ports need to develop at a corresponding pace to avoid becoming a stumbling block. This paper analysed the opportunities and challenges faced by H₂ ports in the context of Australia and Japan.

Opportunities for ports in the H₂ economy include business transition processes, H₂ production, increasing trade, improving utilisation of port infrastructure, and applying H₂ to powering port assets. With the opportunities, ports' major roles within the emerging global H₂ supply chains include ensuring sufficient infrastructure and facilities to facilitate the trade of different forms of H₂ and other imported equipment for producing H₂; the decarbonisation of port assets by using H₂; the facilitation of the domestic use of H₂ to decarbonise the region; and coordination and collaboration with other stakeholders to ensure a safe H₂ supply chain.

However, ports face challenges. These include land use, uncertainty about H₂ demand, the lack of adequate infrastructure, insufficient education on H₂ knowledge and technology, the lack of safety standards and regulations, and obtaining social licence. Ports considering applying H₂ face challenges of regulatory support and costs associated with investment. Scaling up H₂ transport using large carriers requires port infrastructure development, such as large storage tanks to accept them. The interview results also revealed that the government support for ports falls short of what is needed.

The survey outcomes revealed that the sufficiency level of the port infrastructure and facilities in both countries is below acceptable levels. The results imply that overall port infrastructure and facility development for H₂ ports is in an early stage. Similarly, for the readiness level of critical factors, most of the survey participants thought they were at a development stage or below.

To address the challenges, this research provided several recommendations. Also, for ports seeking to embrace H₂, this research developed a comprehensive operational framework to provide valuable guidance. The framework emphasises a user-oriented working process that considers the specific needs and requirements of the port. Government support is considered a crucial factor, with the framework highlighting the importance of policies, incentives, regulations, community/social engagements, and green certification to facilitate the transformation of ports into H₂ ports.

This study builds on the current state of the art by integrating the latest developments in green H₂ technology and infrastructure. The identified academic contributions highlight the importance of firsthand empirical data in understanding and advancing H₂ ports. By employing a mixed-methods approach, this research fills significant gaps in the literature, providing practical insights into the readiness and requirements of ports in the H₂ economy. Furthermore, the operational framework proposed in this study addresses both theoretical

and practical aspects, offering a comprehensive guide for policymakers, port authorities, and industry stakeholders. These contributions not only advance academic discourse but also provide actionable solutions to real-world challenges, positioning ports as critical hubs in the global H₂ supply chain.

Due to the nascent stage of H₂ ports, the limited number of survey respondents in this study poses a limitation. This scarcity of knowledgeable respondents inherently limits the scope of data collection efforts. Additionally, the respondents' perspectives may not capture the full range of potential issues, challenges, and opportunities that could be encountered as the hydrogen infrastructure matures. Therefore, while the insights gathered are valuable, they represent a preliminary understanding rather than a comprehensive analysis. Given the constraints of the survey, it is essential to interpret the survey findings with caution. The limited sample size means that the results should be viewed as indicative rather than conclusive. They provide a snapshot of perceptions and experiences, which can inform the initial stages of planning and development but should not be overgeneralised.

Nonetheless, the findings of this study can provide directions for further research. First, as H₂ ports advance and stakeholders accumulate knowledge and experience, it will be necessary to undertake more extensive empirical studies covering more countries to gain a deeper understanding of the progress made in H₂ ports. Second, this research has provided general recommendations for planning and implementing H₂ ports. Further studies could be focused on developing detailed strategies and concrete solutions to address the challenges. Finally, future research could entail conducting meticulous investigations into the domain of safety risk management within H₂ ports, thereby establishing a robust framework to underpin the development of port-specific H₂ regulations, standards, or safety protocols. In the future, with the further development of H₂ ports and supply chains, the findings, including the proposed operational framework, could be better tested and generalised in practice.

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

Abbreviations

H ₂	Hydrogen
GHG	Greenhouse gas
CH ₂	Compressed hydrogen
EU	European Union
IAPH	International Association of Ports and Harbors
IEC	International Electrotechnical Commission
IMO	International Maritime Organization
ISO	International Organization for Standardization

LH ₂	Liquid hydrogen
LNG	Liquified natural gas
LOHCs	Liquid organic hydrogen carriers
MCH	Methylcyclohexane
METI	Ministry of Economy, Trade and Industry of Japan
NASA	US National Aeronautics and Space Administration
SIGTTO	Society of International Gas Tanker and Terminal Operators
TRL	Technology Readiness Level

Appendix A

Table A1. Interview guide.

Key Words	Interview Question	Group
Opportunities	(1) Which forms of H ₂ or its derivatives (for example, ammonia, and methanol) are you focusing on? What are the potential markets?	A, B
Opportunities	(2) What opportunities will be brought to ports through the involvement in the H ₂ supply chains?	A, D
Functions	(3) Which port do you plan to use for exporting/importing H ₂ and its derivatives? What functions can the port play to help manage your exporting/importing H ₂ and its derivatives?	B
Functions	(4) What infrastructure and facilities are required for ports to facilitate H ₂ (and its derivatives) trade?	A, B, C
Functions	(5) What types of ships can carry H ₂ and its derivatives? Does your company consider investing in ships for carrying H ₂ or its derivatives?	C
Operations	(6) What operational risks will be in managing H ₂ and its derivatives in ports?	A, B, C
Operations	(7) What level and type of training and education do you need?	A, C
Standards	(8) Below are questions related to standards of H ₂ ports: a. Are there any standard gaps in H ₂ and its derivatives operation and application? b. What should be the key standards for H ₂ ports? c. Do you consider developing specific risk management protocols for H ₂ and its derivatives? d. Do you think there should be global standards for integrating ports into global H ₂ supply chains? What should be standardised? e. What actions should government agencies (national and international) undertake to ensure a safe H ₂ port?	A, B, C, D
Challenges	(9) What are the challenges to ports in managing the export/import of H ₂ and its derivatives?	A, B, C
Challenges	(10) Do you consider applying H ₂ to power port assets as a strategy to decarbonisation? What are potential barriers/challenges to the application? How would you manage them?	A
Challenges	(11) Does your port consider building H ₂ supply infrastructures? For example, H ₂ refuelling stations. Do you consider providing H ₂ -based alternative fuel bunkering service, such as ammonia and methanol? What will be the barriers to such development?	A
Challenges	(12) What are the major challenges in carrying H ₂ and its derivatives on board?	C
Challenges	(13) What are the biggest challenges to shipping and ports in the global H ₂ supply chain?	C
Challenges	(14) What are your region's key challenges to developing a H ₂ port (i.e., managing H ₂ logistics and applying H ₂ technology to power port assets)?	D
Supports	(15) What kind of support should government agencies provide for the operation and application of H ₂ or its derivatives at ports? (e.g., policy and legal framework, future strategy)	A, B, C
Supports	(16) What kind of support has the government provided or planned for the operation and application of H ₂ or its derivatives in ports? How do you coordinate and collaborate with key stakeholders to develop H ₂ ports?	D

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