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Integration of Ports in Global Hydrogen Supply Chains : Opportunities and Challenges

By

Australian Maritime College／University of Tasmania

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Theme 2: Maritime transport for sustainable development

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Abstract This research project investigated the opportunities and challenges in integrating ports into hydrogen (H2) supply chains and applying H2 as energy in ports in the context of Australia, Japan, and the United Kingdom. A comprehensive literature review, qualitative interviews, and a quantitative online survey were conducted to assess the current state of the H2 industry, identify potential H2 ports, determine the necessary infrastructure and facilities required for H2 integration, evaluate the readiness levels of key factors for operating H2 ports, and assess the operational risks associated with H2 handling and utilisation in ports. Recommendations were proposed to address the challenges and barriers encountered by ports. To optimise logistics operations within H2 ports and facilitate effective integration of H2 applications, this project developed a user-oriented working process framework to provide guidance to ports seeking to engage in the H2 economy. The findings and recommendations of this research contribute significantly to filling the existing knowledge gap pertaining to H2 ports.

Keywords: *Maritime, Energy, Hydrogen, Ammonia, Methanol, Liquid Organic Hydrogen Carriers (LOHCs), Supply chain, H2 Port, Readiness, Risk.*

Executive summary

Ports play a crucial role in the global supply chain and transportation network, serving as vital hubs for trade and commerce. With the growing demand for hydrogen (H2) worldwide, ports have an opportunity to leverage their strategic location, infrastructure, and expertise to facilitate international H2 trade. Moreover, ports have the potential to become consumers of H2 as a source of energy for their operations, thereby reducing their carbon footprint. As such, the term 'H2 port' is used in this research project, referring to ports that engage in transport logistics and application functions in the hydrogen supply chain. Currently, H2 ports are still in their early stages, and there is a need to fully understand their functions and the challenges facing them. To bridge the knowledge gap in H2 ports, this project selected ports in Australia, Japan, and the UK as research subjects to explore how ports can be integrated into H2 supply chains and how they can be utilised on their operations using H2.

This project employed a comprehensive research approach, encompassing a thorough review of the literature, in-depth interviews, and an online survey. The methodology enabled examining the current state of the H2 industry globally particularly Australia, Japan, and the UK, identifying potential early H2 ports, determining required infrastructure and facilities and their sufficiency for the successful establishment of H2 ports, assessing the readiness levels of critical factors for operating H2 ports, and evaluating operational risks associated with H2 in ports. To streamline logistics operations and effectively integrate H2 applications in ports, a framework was developed based on the empirical study results. This project also provided recommendations for managing the challenges to H2 ports.

Through the literature review, this project depicted a port-focused international hydrogen supply chains with their features according to different technology pathways, i.e., liquid hydrogen, ammonia, methanol, and liquid organic hydrogen carrier (LOHC), the suitable forms of hydrogen for international trade. The review also identified five possible earlier exporting countries including Australia, Chile, Mauritania, Saudi Arabia, and Norway, and six possible early importing countries including Germany, the UK, the Netherlands, Japan, South Korea, and Singapore. Twenty ports that could be the first movers of hydrogen trade were also revealed. In relation to ports applying H2, the literature review illustrated eighteen ports in thirteen countries that have hydrogen application projects, such as in-port hydrogen-powered vehicles, ships, and portable power supply units being tested or demonstrated.

Twenty-seven semi-structured interviews were conducted by this research with senior managers of port companies/authorities, terminal operators, producers/exporters/importers of H2 and its derivatives, shipping companies and government agencies in Australia, Japan, and the UK. The interview outcomes revealed the opportunities for ports in the H2 economy, i.e., business transition, increasing trade, improving utilisation of port infrastructure, supporting renewable energy's development, being resilient in terms of mixed energies for customers, and applying H2 in port assets. The results also indicated challenges faced by ports in facilitating H2 logistics and application, including land use, uncertainty of H2 demand, lack of adequate infrastructure, insufficient education on H2 knowledge and technology, lack of safety standards and regulations, obtaining social licence, lack of regulatory support, and costs associated with investment.

Twenty-two online survey responses were collected from senior managers from port companies/authorities and operators, producers, exporters, and importers of H2 and its derivatives in Australia, Japan and the UK. The survey results revealed that safety equipment, monitoring and control systems being the most required infrastructure and facilities for H2 ports, followed by storage tanks, loading/unloading facilities, berths, liquification facilities, pipelines (normal temperature and cryogenic temperature), but their sufficiency level in the three countries were below the acceptable range (scale 5). For the readiness level of critical factors for H2 ports i.e., regulations and standards, infrastructure, safety measures, personnel training, and government support, most of the survey participants thought they were at a development stage or below across the three countries except berths about 5 in Japan and the UK. Most of the survey participants considered that in a 10-year timeframe, ammonia was expected to be the primary carrier of H2 and traded through ports. Cryogenic LH2 was ranked second, although

there are significant challenges to overcome in terms of large-scale storage technology, and methanol was ranked the third. The survey results also indicated that many participants preferred dedicated berths for facilitating H2 and its derivatives. The risk matrixes generated based on the survey participants' perceptions on LH2 and GH2's operational risks in ports showed that both GH2 and LH2 operations within the port area do not have any hazardous events reaching the highest risk level, but there are some events that reach "Substantial" and "Moderate" risk levels, requiring mitigation risk measures.

As a result of the literature review, interviews and online survey, this project identified nineteen potential H2 ports in Australia, Japan, and the UK. Ten ports in Australia, six in Japan, and three in the UK. The Australian ports primarily serve as exporting ports, while Japanese ports function as importing ports. The UK ports currently have the potential to serve as importing ports in the short term, with the possibility of transitioning into exporting ports as the country's H2 production scales up. The empirical study result also enabled developing a comprehensive operational framework to provide valuable guidance for H2 ports. The framework emphasises a user-oriented working process that considers the specific needs and requirements of the port. Additionally, 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.

Seven recommendations were provided for managing challenges and barriers to ports involving in the H2 supply chains, based on the empirical research results. These included increasing accessibility of resources, accelerating port infrastructure development, increasing incentives for ports to support decarbonisation, adopting stakeholder collaboration approach for establishing regulations and standards, enhancing understanding of H2 safety, developing practical personnel training, and promoting public awareness to facilitate obtaining social licence. Key strategies of each recommendation are highlighted below.

- Improving stakeholder communication and negotiation to secure land, collaborating with renewable energy providers for reliable electricity supply through grid upgrades, and actively exploring alternative water sources like desalinated seawater to ensure sufficient supply for H2 production.
- Existing infrastructure and facilities can be utilised for ammonia, methanol, and LOHCs, enabling the initiation of demonstration projects in the near future. However, technological breakthroughs are required for LH2 infrastructure. Developing berth management protocols that address both short-term common-use berths and long-term dedicated berths is advisable.
- Providing incentives such as financial and tax reduction for ports that contribute to reducing GHG emissions to encourage ports to use H2 as source of energy.
- Governments and regulatory bodies (international or national) should collaborate to establish port-specific regulations and standards for H2 handling, infrastructure, safety, and environmental aspects. For example, The IMO can play a role to internationally coordinate shipping and ports/terminals for H2 transport.
- Share experience and collaborate with industries of expertise in handling hazardous materials that can help develop robust safety protocols for H2 in ports. Knowledge gained from the aerospace and LNG industries can be a valuable reference. NASA's H2 safety standards system can serve as a significant reference for ensuring safety in H2 ports. The regulatory framework for LNG ships by the IMO and the comprehensive standard system established by the Society of International Gas Tanker and Terminal Operators (SIGTTO) can provide guidance for the safe construction and operations of H2 ports and shipping.
- It would be beneficial to engage professional experts from the aerospace industry who can provide practical knowledge and hands-on training exercises to enhance the skill set of port professionals in the H2 sector.
- Through public education campaigns, conducting independent studies on H2 ports, and actively engaging the local community in project planning and decision-making processes can help promote public awareness of the social, economic, and environmental impacts of H2 ports.

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List of Abbreviations

ADR	The Agreement concerning the International Carriage of Dangerous Goods by Road
AMLRN	The Australian Maritime Logistics Research Network
AMSA	The Australian Maritime Safety Authority
ARENA	The Australian Renewable Energy Agency
CAPEX	Capital expenditure
CH2	Compressed hydrogen gas
CNP	Carbon neutral port
CO2	Carbon dioxide
DBT	Dibenzyl toluene
ESG	Environment, social, and governance
EU	European Union
FC	Fuel cell
GHG	Greenhouse gas
GW	Gigawatts
GX	Green transformation
H2	Hydrogen
HAZID	Hazard identification
HE	Hazardous event
HSE	The health and safety executive
IAMU	The International Association of Maritime Universities
IAPH	The International Associations of Ports and Harbours
IDLH	Immediately dangerous to life or health
IEA	The International Energy Agency
IEC	The International Electrotechnical Commission
IGF CODE	The international code of safety for ship using gases or other low-flashpoint fuels
IMO	The International Maritime Organization
IRA	The inflation reduction act
ISO	The International Organization for Standardization
LH2	Cryogenic liquid hydrogen
LNG	Liquified natural gas
LOHCs	Liquid organic hydrogen carriers
LPG	Liquefied petroleum gas
MCA	Maritime and coastguard agency
MCH	Methylcyclohexane
METI	Ministry of Economy, Trade and Industry of Japan
MT	Million tons
MW	Megawatts
NASA	The National Aeronautics and Space Administration
NDC	Nationally determined contributions
NEDO	The New Energy and Industrial Technology Development Organization
NFPA	The National Fire Protection Association
NIMBY	Not in my back yard
OPEX	Operational expenditure

RQ	Research question
RTG	Rubber-tired gantry
SIGTTO	The Society of International Gas Tanker and Terminal Operators
TPI	Toxicity potential indicator
UK	The United Kingdom

1. Introduction

1.1 Background and Objectives

The Paris Agreement signatories have submitted their Nationally Determined Contributions (NDC) to address climate change. According to the online database "Net zero Tracker" [1], as of May 2023, 128 countries had set or proposed net-zero greenhouse gas (GHG) emissions targets. Most countries set targets to achieve net-zero by 2050 or 2060. To this end, the use of hydrogen (H2) is expected to be one of the key decarbonisation options. The main reason is that H2 is an excellent carrier of renewable energies, such as wind, solar and hydropower, which can be released as heat through combustion, or as electricity using fuel cells (FCs), in both cases the only other input needed is oxygen, and the only by-product is water. Therefore, H2 has the potential to replace fossil fuels in some scenarios. Many countries issued their H2 strategies [2, 3]. Sixteen out of the top 20 GHG emission countries, which are responsible for 78.11% of global emissions [4], have clearly raised H2 to the level of national energy strategies and have formulated relatively straightforward timetables and roadmaps. According to the literature [5-7], H2 could account for 10-18% of the global energy consumption mix by 2050.

The worldwide H2 demand, the renewable energy resource endowments, unbalanced H2 production costs, and geopolitical factors drive the formation of international H2 trade [8, 9]. Therefore, the potential of the international H2 supply chains is vast, and it is expected to form a new international energy supply pattern. The main pillars of the H2 supply chains are production, storage, transportation, and utilisation [10]. The H2 supply chains are more complicated than others because of numerous permutations of how H2 being produced, stored, transported, and utilised, all of which differ in technology, infrastructure, and safety. In the existing literature, many studies have demonstrated the diversity of H2 supply chains in terms of production [11-15], storage [16-18], transportation [19-24], and utilisation [25-29].

Ports are an important infrastructure within the supply chain, and hence the development of hydrogen industry will bring potentials for ports through different activities. They facilitate hydrogen transport logistics either for export or import, such as handling and bunkering. Besides, ports are significant GHG emitters. To achieve deep decarbonisation, one promising option for ports is to utilise H2 as an energy source for their assets, including in-port vehicles, machinery, and vessels. Other potential is that many ports have access to H2 production resources, such as wind and solar power; hence they can be good locations to produce hydrogen. Therefore, ports could be a hub of the hydrogen industry from production to consumption. Furthermore, since most ports are in core economic areas, the application of H2 energy can be extended beyond the ports themselves. This expansion can include surrounding cities and industrial areas, resulting in further decarbonisation of local economies. Despite the potential for ports, there will be challenges in operation such as infrastructure and facility development, safety, government policy and regulations, and community concerns.

With the emerging international hydrogen trade, ports play vital roles in developing a sustainable hydrogen economy and supply chain. However, there is limited literature focused on ports in the H2 supply chains. Hence, ports' opportunities and challenges require investigation. This research explores how ports can be integrated in H2 supply chains. It focuses on two areas: firstly, ports' involvement in logistics services provision to H2 as a commodity, and to ships adopting H2 (bunkering); secondly, ports' role as an enabler of H2 application in powering available assets to commit to the reduction of GHG or become a CO2 neutral port. The focused areas 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 the functions.

There are two research questions (RQ) in this study:

- RQ1: How can ports become a logistics centre to best facilitate H2 trade?
- RQ2: How can ports achieve carbon neutral by adopting H2 technology?

In answering the RQs, this research achieves the following objectives.

- Determine the infrastructure and facilities required for ports to facilitate H2 logistics both for import and export.
- Evaluate risks of H2 logistics operation in ports.
- Identify the challenges and barriers associated with adopting H2 technology in ports and terminals.
- Develop a framework for logistics operation and application of H2 in ports, including working process, handling, training, and safety.
- Provide recommendations to address the current challenges and barriers related to handling H2 in ports.

This project took Australia, Japan, and the United Kingdom (UK) ports as research subjects. The three countries are at the forefront of H2 industry development globally. The research conclusions obtained by studying them have certain representativeness and will have reference value for developing H2 ports worldwide.

1.2 Research Approach

The research project undertook the following steps to achieve the research objectives.

- Reviewed literature, including academic, industry, government publications and reports.
- Interviewed key stakeholders including H2 producers/exporters/importers, port managers/operators, shipping companies, and government agencies in Australia, Japan, and the UK to explore the H2 ports' opportunities and challenges qualitatively. A potential Australian H2 Port was visited.
- Conducted an online survey in the three countries to investigate the readiness levels of infrastructure and critical factors required for, and operational risks of H2 ports quantitatively.
- Developed a framework for operating H2 logistics and application of H2 technology in ports.
- Provided recommendations for the development of H2 ports.

1.3 Research Outputs

The research project has produced the following outcomes.

- This final report.
- A journal paper titled 'A review on ports' readiness to facilitate international hydrogen trade' has been published in the International Journal of Hydrogen Energy, Volume 48, Issue 46, 29 May 2023, Pages 17351-17369, (DOI: https://doi.org/10.1016/j.ijhydene.2023.01.220).
- A conference paper titled 'Ports and hydrogen supply chains' has been presented at the Australian Maritime Logistics Research Network (AMLRN) 2022 Symposium.
- A presentation titled 'Ports' role in the hydrogen economy' has been presented at the PIANC Tasmania Conference April 2023.
- A conference paper titled 'Hydrogen Shipping Cost Evaluation for Potential Routes' has been submitted to IAMU Conference 2023 in Helsinki Finland.
- A journal paper titled 'An empirical study of hydrogen ports' opportunities and challenges' is about to submit to the International Journal of Hydrogen Energy.

1.4 Structure of the Report

The report consists of seven (7) sections.

Section 1 introduces the background and objectives of this project. It describes the approach carried out to achieve the objectives and summarises the outputs of this project.

Section 2 outlines the status of the development of the H2 industry in the three countries. It forms the basis for the literature review and selection of interviewees and survey participants.

Section 3 conducts a literature review to explore the status of exporting/importing H2 through ports and adopting H2 in ports in terms of infrastructure, risk, public acceptance, regulation and standard development, and education and training.

Section 4 presents the results and findings from interviews with key stakeholders. It provides a comprehensive understanding of the opportunities and challenges that arise in handling and using H2 and its derivatives in ports and recommends solutions to overcome the challenges.
Section 5 presents the results of the online questionnaire survey. It provides a quantitative understanding of the status of ports' infrastructure and facilities, and operational risks associated with H2 handling and use in ports.
Section 6 suggests a framework for operating H2 logistics and applying H2 technology in ports.
Section 7 recommends strategies for overcoming the challenges and barriers faced by H2 ports. It then concludes the report with suggestions for further research.

2. Overview of the Development of the Hydrogen Industry

This section outlines the status of the H2 industry, particularly in Australia, Japan, and the UK. It lays the foundation for the subsequent literature review, interviews, and questionnaire surveys for this study. Generally, the formation of zero-emission H2 economy needs to go through the following stages:

- Stage 1: Generate sufficient zero-emission electricity or import sufficient zero-emissions H2 or H2-based fuels to replace the existing coal and natural gas fuelled power generations.
- Stage 2: Generate more zero-emission electricity or import more H2 or H2-based fuels to be used for stationary energy and transport sector.
- Stage 3: Generate more zero-emission electricity to produce H2 or import more H2 for where electrons are not ideal and high-density molecular fuel is needed, or to replace natural gas and coal in some cases as a chemical feedstock for industry.
- Stage 4: Generate more zero-emission electricity to produce H2 or import H2 to produce goods that embody large amounts of energy, such as steel and cement.
- Stage 5: Generate more zero-emission electricity to produce H2 for export.

Fortunately, these stages are happening in parallel in some countries depending on their energy structures.

The top 20 GHG emission countries, which are responsible for 78.11% of global emissions [4], were reviewed. As presented in Tab. 1, 16 out of the 20 countries clearly raised H2 energy to the level of national energy strategies and formulated relatively straightforward timetables and roadmaps. They promote the development of H2 energy from multiple perspectives, including in-depth assessment and exploration of the potential markets, comprehensive promotion of H2 energy technology research and development, standardising the H2 energy industry, building the H2 supply chains, and strengthening worldwide H2 energy cooperation.

Tab. 1 National hydrogen strategies and roadmaps

Government	Title	Ref.
China (1*)	Medium and Long-Term Plan for the Development of Hydrogen Energy Industry (2021-2035)	[33, 34]
US (2)	DOE National Clean Hydrogen Strategy and Roadmap	[35]
India (3)	National Hydrogen Mission	[36]
Russia (4)	Concept for the Development of Hydrogen Energy in Russia 2021	[37]
Japan (5)	Basic Hydrogen Strategy	[38]
Germany (6)	The National Hydrogen Strategy	[39]
South Korea (8)	Hydrogen Economy Roadmap of Korea	[40, 41]
Saudi Arabia (10)	National Hydrogen Strategy (under development)	[42]
Canada (11)	Hydrogen Strategy for Canada	[43]
South Africa (12)	Hydrogen Society Roadmap for South Africa 2021	[44, 45]
Brazil (14)	National Energy Plans 2050	[46]
Australia (15)	Australia's National Hydrogen Strategy State/territory Hydrogen Strategies	[47-55]
UK (17)	UK Hydrogen Strategy	[56, 57]
Italy (18)	National Hydrogen Strategy Preliminary Guidelines	[58]
Poland (19)	Polish Hydrogen Strategy to the Year 2030 with an Outlook to the Year 2040	[59, 60]
France (20)	National Strategy for the Development of Decarbonised and Renewable Hydrogen in France	[61]

*Note: * The number in parentheses represent the global ranking of GHG emissions* [4].

According to the International Energy Agency (IEA), as of October 2022, a total of 1,467 H2 production projects had been officially announced worldwide [30]. The capacities of these projects were synthesised in this study, and the 47 countries with announced zero-carbon H2 production capacity greater than 1 ton/hour are shown in Fig. 1. The total announced capacity is 8,625 tons/hour. Assuming 80% of the capacity will be in operation, the annual production is equivalent to 56.37 Mt. The IEA projects that global annual H2 demand will be more than 200 Mt in 2030 and 530 Mt in 2050 [31, 32]. The proportion of low-carbon H2 will rise to 70% in 2030 and about 90% in 2050 [6]. Therefore, the announced zero-carbon H2 production capacity (56.37 Mt/year) meets about 40% of the demand in 2030 and about 12% in 2050. This data shows the positive progress of the H2 industry. Fig. 2 presents the top 20 countries and their capacities.

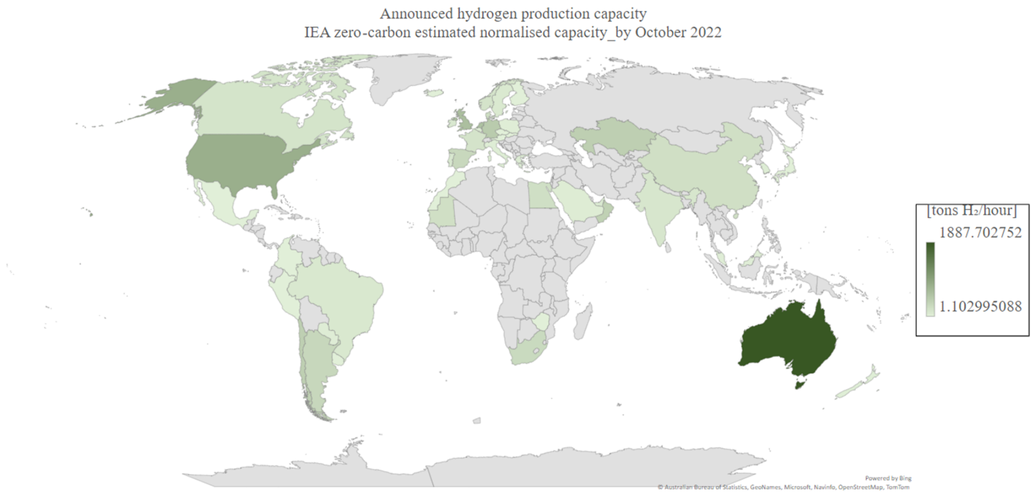


Fig. 1 Announced zero-carbon estimated normalised hydrogen production capacity

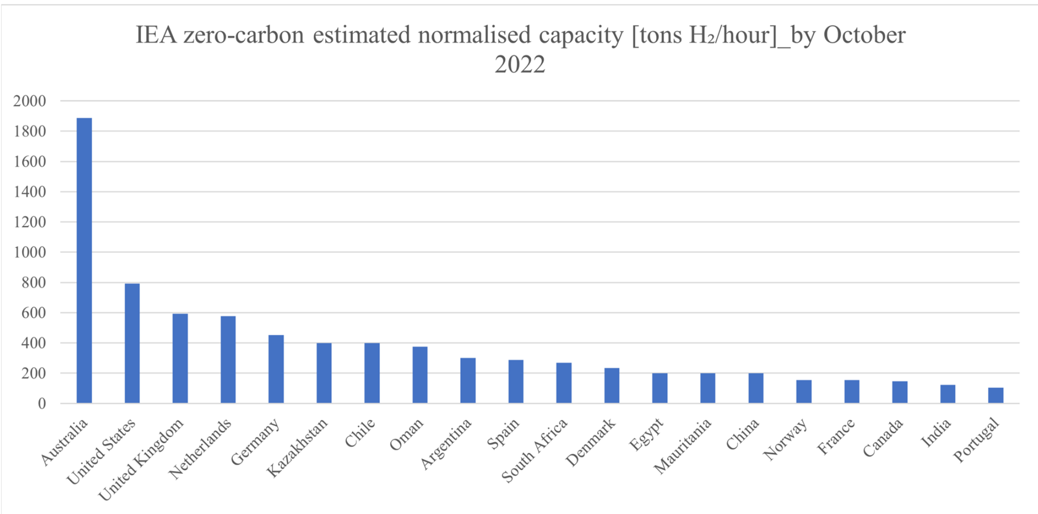


Fig. 2 Top 20 countries by announced zero-carbon estimated normalised hydrogen production capacity

The below subsections introduce the development of the H2 industry in Australia, Japan and the UK.

2.1 Australia

Australia has rich renewable energy resources and a small population relative to land mass, producing H2 to export is feasible. From 2019 to 2022, the federal, state, and territory governments issued many announcements on H2 strategies, as presented in Tab. 2.

Tab. 2 Australian federal and state/territory hydrogen strategies

Government	Title	Ref.
Federal	Australia's National Hydrogen Strategy	[47, 48]
Queensland	Queensland Hydrogen Industry Strategy	[49]
New South Wales	NSW Hydrogen Strategy	[50]
Victoria	Renewable Hydrogen Industry Development Plan	[51]
Tasmania	Tasmanian Renewable Hydrogen Action Plan	[52]
South Australia	South Australia's Hydrogen Action Plan	[53]
Western Australian	Western Australian Renewable Hydrogen Strategy	[54]
Northern Territory	Northern Territory Renewable Hydrogen Master Plan	[55]

These strategies involve Australia's bold vision of becoming a major H2 economy and exporter [62]. For example, a key aim of the Australia's National Hydrogen Strategy is for the country to become one of the top three H2 exporters to Asian markets by 2030 [48]. Seven H2 hub regions were identified and funded by the federal government, i.e., Bell Bay in Tasmania, Pilbara in Western Australia, Gladstone in Queensland, La Trobe Valley in Victoria, Eyre Peninsula in South Australia, Hunter Valley in New South Wales, and Darwin in Northern Territory (Fig. 3) [63]. The government has invested A$464 million in H2 hubs as part of its A$1.2 billion commitment towards building a H2 industry. Australia's policies and projects are ever growing, the information can be found on an online information-sharing portal HyResource [64]. The cost of producing clean H2 in Australia is expected to be A$2.30-5.00/kg ($1.60-3.49/kg) in 2025, and A$2.00-4.00/kg ($1.39-2.79/kg) in 2030 [65], making the country a competitive exporter. In practice, Australia, collaborating with Japan, completed the first trial of shipping Liquified hydrogen (LH2) to the Port of Kobe in Japan from Victoria's Port of Hastings in 2022 [66]. The port of Geelong in Victoria plans to spend A$100 million on a green H2 hub, including green ammonia (a type of H2 derivative) capacity for export to Asia [67]. The Port of Bonython is being developed as a major H2 and ammonia export hub of the South Australia [68]. The Port of Newcastle received funding to establish an initial 40 MW H2 production hub, with plans to explore future expansion up to 1 GW capacity (equivalent to 0.15 Mt per year) for both domestic consumption and export purposes [69]. The Western Australia government plans to create five H2 hubs from Onslow to the Port of Hedland by 2030 [70]. The Port of Bell Bay in Tasmania plans to be a leading producer and exporter of green H2 [52], with 1,000 MW green ammonia and 120 MW green methanol (both are types of H2 derivative) production capacities to be delivered. The Port of Darwin in Northern Territory would become a H2 exporting port as the Darwin H2 hub plans to build a 1 GW electrolyser to produce more than 0.08 Mt of green H2 per year to support exports into the Indo-Pacific [71]. The Port of Rotterdam has signed agreements with four Australian state governments to explore the possibility of importing H2, including South Australia [72], Queensland [73], Western Australia [74], and Tasmania [75]. It is estimated that the demand for H2 exported from Australia will be at over 3 Mt per year by 2040 [76].

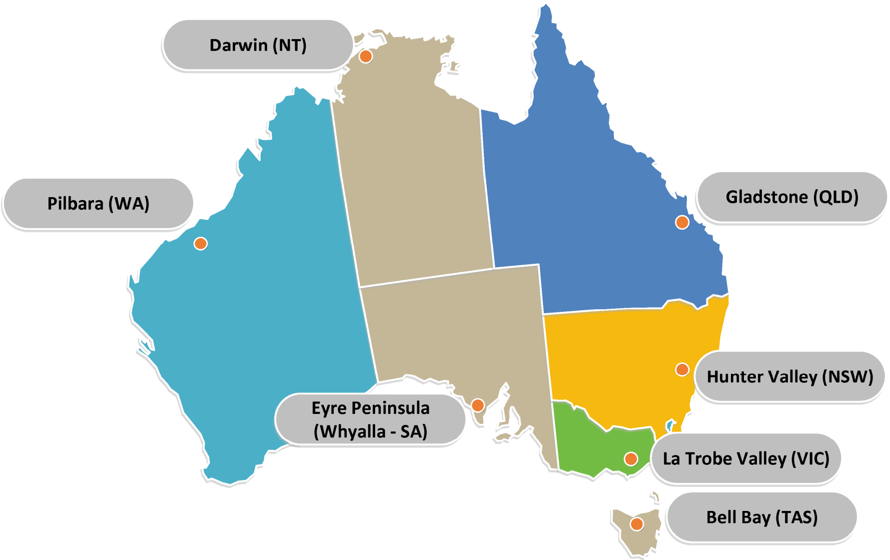


Fig. 3 Seven hydrogen hubs in Australia

2.2 Japan

Japan issued its Basic Hydrogen Strategy in 2017 [77], stating H2 import infrastructure would be developed. The main contents of the strategy are:

- Phase 1: Dramatic expansion of H2 use (from 2016); Phase 2: Full-fledged introduction of H2 power generation and establishment of a large-scale H2 supply system (by the second half of the 2020s); Phase 3: Establishment of a carbon dioxide (CO2) free H2 supply system on a total basis (by around 2040).
- It aims to create viable international H2 supply chains and establish upstream initiatives to secure cheap overseas resources.
- It focuses on H2 carriers such as methylcyclohexane (MCH), ammonia, and methane in addition to LH2.
- It aims to reduce retail price of H2 to $0.27/Nm3 ($1.36/kg) by 2030 and to $0.17/Nm3 ($0.86/kg) in the long-term from current $0.90/Nm3 ($4.54/kg).

Japan's H2 demand will reach up to 3.0 Mt/year by 2030 and 20 Mt/year by 2050, mainly from overseas [77, 78]. The country has established supply chains cooperation with Australia, Brunei, and Saudi Arabia [79, 80]. Importing H2 in the forms of LH2, Liquid Organic Hydrogen Carriers (LOHCs), and ammonia are expected in Japan [81]. The first H2 shipments from Australia via LH2 in 2022, from Saudi Arabia via ammonia ISO tanks in 2021, and from Brunei via LOHC ISO tanks in 2020 demonstrated the feasibility of the H2 shipping [66, 82, 83]. Japan's Kobe port and Onahama port are exploring their future H2 and ammonia import potential [84, 85].

The development progress of the H2 energy application market in Japan is at the forefront of the world. For example, as of February of 2023, H2 refuelling stations scattered nearly all prefectures in Japan, as presented in Fig. 4 [86].

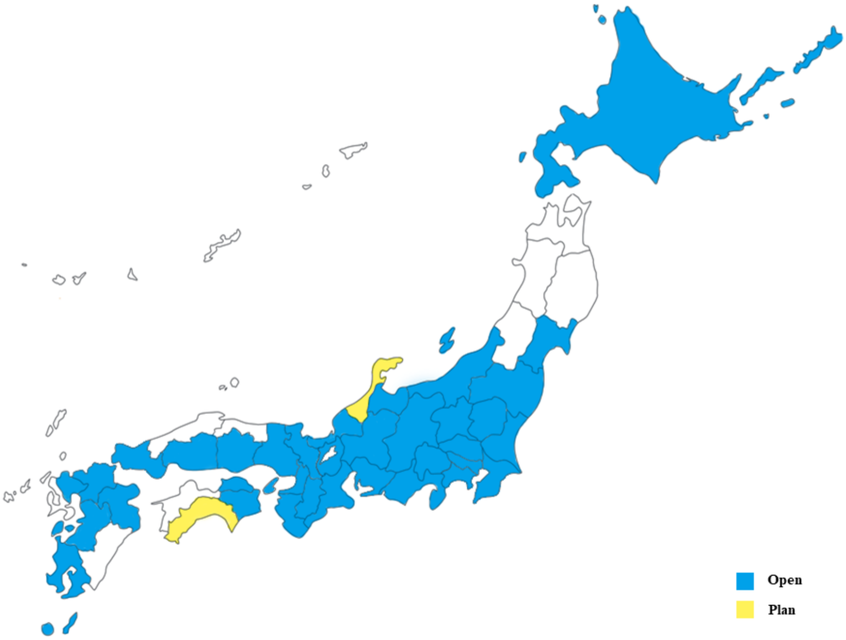


Fig. 4 Hydrogen refuelling station deployment in Japan

2.3 The United Kingdom

The UK issued the country's Hydrogen Strategy in 2021 [56] with the aim to:

- Decarbonise transport and industry using both green and blue H2.
- Develop 5 GW of low carbon H2 production capacity by 2030.
- Make H2-based energy to reach 20-35% of the UK's energy consumption by 2050.

In April 2022, the UK government announced an "ambition" for up to 10GW of green and blue H2 production capacity by 2030, doubled the previous target [56, 57]. The country needs around 7.6-13.9 Mt of low-carbon H2 by 2050 [56]. The current H2 production capacity is 0.3-0.8 Mt, and only a fraction of them is low-carbon H2 [87, 88]. Therefore, in the short term, the UK could be an H2 importer to lower the risks of meeting expected demand. For example, the Port of Cromarty Firth is planning to import green H2 from Norway [89]. However, in the long term, the government has an ambition to become an exporter, with a report on its H2 export capability issued [90]. In April 2023, the Energy Networks Association published a report "A hydrogen vision for the UK" [91]. It summarised the major H2 projects encompassing production and utilisation in the UK, as shown in Fig. 5. The projects focus on using hydrogen to provide heat for distillation, decarbonise food production operations, UK business ports and the sugar refining process, replace natural gas with hydrogen to power toilet paper factory, produce green hydrogen to power hydrogen buses in Northern Irland, use electrolytic hydrogen facility with opportunity to support GW scale offshore floating offshore wind, and establish zero emission development centre for hydrogen technology.

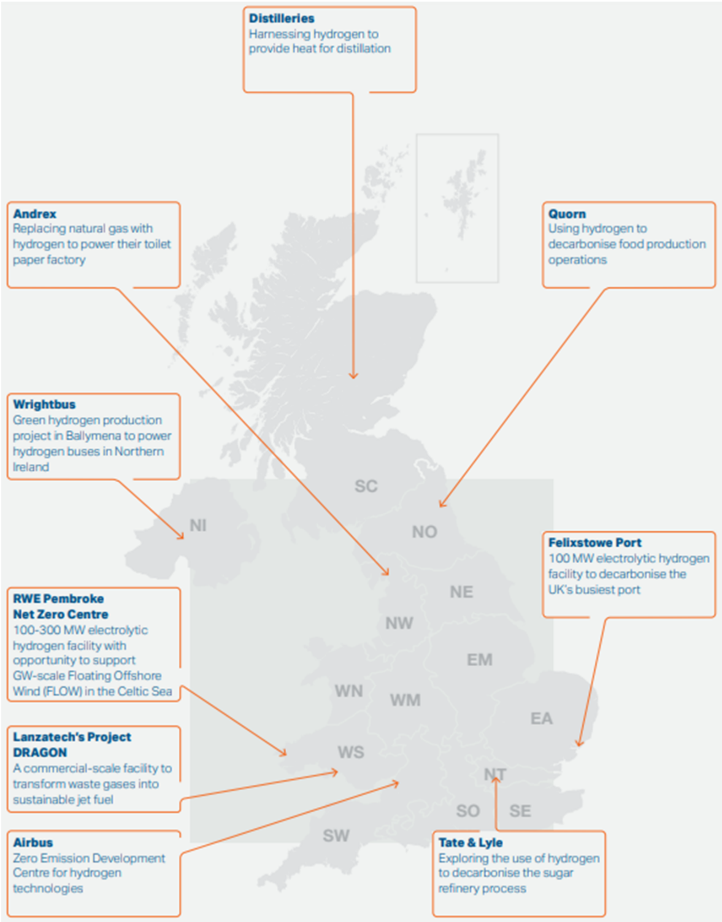


Fig. 5 Major hydrogen projects in the UK [91]

3. Literature Review

This section reviews academic and grey literature, including journal articles, government documents, government websites, media, and industrial reports, to investigate ports' readiness for facilitating international H2 trade and the status of adopting H2 in ports.

3.1 Hydrogen Supply Chains

The key functions and links in a typical H2 supply chain include production, conversion, storage, transport, distribution, re-conversion, and utilisation, as shown in Fig. 6. The production of H2 is referred to in different colours that may result in different supply chain processes. For example, black and brown H2 is produced from coal (bituminous or lignite) with a large quantity of CO2 emissions. Grey H2 is obtained by steam reforming fossil fuels with significant CO2 emissions. Blue H2 is sourced from fossil fuels, however, the CO2 is captured and stored with carbon capture and storage technologies. Green is used to describe H2 that is produced on a CO2-neutral basis through water electrolysis. Global annual H2 production was about 75 million tons (Mt) of pure H2 and about 45 Mt mixed with other gases and used in industries in 2020 [6]. About 50% of annual pure H2 production was used as a feedstock in producing nitrogen fertilisers and about 25% was converted to low-grade crude oils and then into liquid transport fuels. Almost 96% of all H2 produced was black, brown, or grey [92]. Fossil fuel based H2 production will gradually phase out, nevertheless, in the short term, blue H2 is still positioned to act as a bridge to green H2 that has yet to be scaled up. Blue H2 has made its way into the official strategies of major economies, like the UK, US, Japan and, the EU countries [93]. Ongoing innovation and scaling up are expected to bring green production process costs down and make it more competitive by 2025 or 2030 [76].

H2, like natural gas, requires conversion for storage and transport because of its low density (0.084 kg/m^3). The conversion can be achieved in three ways: compression [94], liquefaction [95], and chemical compounding [96-98]. Currently, typical pressures of compressed H2 gas (CH2) are 35 MPa (the density is 23 kg/m3) and 70 MPa (the density is 42 kg/m3). H2 turns into a liquid when it is cooled to below -252.87 °C via a liquefaction process. LH2 has a density of 70.8 kg/m3, and its volume is 1/800 of gaseous H2, which increases the efficiency of storage and transport. It has a purity of 99.999% and can be directly supplied to fuel cells (FCs) only by evaporating. The promising chemical compounding forms are ammonia, methanol, or LOHCs [99, 100]. Ammonia is a compound of hydrogen and nitrogen in the form of NH3 synthesised via the Haber-Bosch process [101]. Methanol is an H2 carrier in the form of CH3OH. The reaction of H2 with CO2 to form methanol and water [102]. LOHCs are emerging H2 carriers, H2 is stored inside a LOHC molecule (exothermic hydrogenation) at the starting point of the supply chain. Then, the hydrogenated LOHC is stored and transported. At the point of consumption, H2 is released (endothermic dehydrogenation) and the dehydrogenated LOHC returns to the H2 production point to start a new cycle [103]. These chemical compounding forms can be stored under relatively easy conditions compared to CH2 and LH2. Liquid ammonia can be stored at minus 33 °C under atmospheric pressure or at 0.8−1.0 MPa under atmospheric temperature [104-106]. Methanol and LOHCs can be stored and transported in liquid forms at normal temperature and pressure [20, 107].

H2, in any form, can reach its destinations via pipelines, road tankers, rail tankers or ships. For shipping, ports are the most essential links. The different technical paths of H2 conversion bring about different characteristics of ports and ships.

Distribution is required after the H2 arrives at the port. The shipping is like arteries, while distribution is like capillaries transporting H2 to end users. The distribution modes can be via roads, rails, pipelines, and ships. Bunkering vessels are required if the end users are ships.

The dehydrogenation of LOHCs and gasification of LH2 are necessary re-conversion steps. Ammonia and methanol can be directly used by some end users, however, they may need to be re-converted to pure H2, depending on the end user's energy usage pattern.

At present, H2 can be consumed in FCs [108], internal combustion engines [109], steam turbines [110], gas turbines [111], and burners [112].

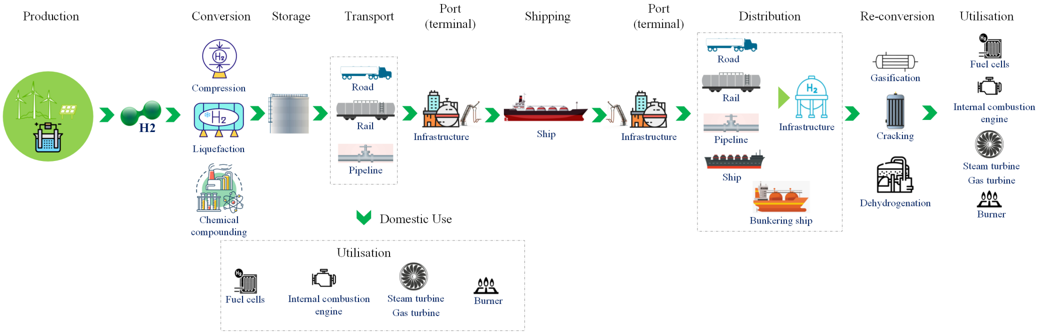


Fig. 6 Hydrogen supply chains

3.2 Ports' Hydrogen Infrastructure

As discussed above, the H2 forms could be CH2, LH2, ammonia, methanol and LOHCs. For international shipping, CH2 is not considered in this literature review due to its low transport efficiency and lack of technological maturity for shipping, even though some conceptual CH2 ships have been designed [113], which might be suitable for some short routes, for example, less than 1,000 km [114]. Therefore, LH2, ammonia, methanol, and LOHCs are the main focuses for international H2 trade.

LH2 has been used in the aerospace industry for decades [115], and micro supply chains have been formed in such countries as US, China, Japan, and Norway [116, 117], laying the foundation for forming large-scale supply chains [118]. The world's first LH2 shipping from Australia to Japan was demonstrated in 2022 [66]. The LH2 ship "Suiso Frontier" received LH2 in the Port of Hastings and returned to Japan, unloading the cargo in the Port of Kobe. LH2 tanks, pipelines, and loading/unloading arms in both ports have been tested. As more conceptual LH2 ships are proposed [119-121], more LH2 ports might be developed. For such exports, liquification facilities are required within or near ports.

Ammonia is a substance that the industry has lots of experience with. There is already significant infrastructure that could be used as a basis for further ammonia trade as a H2 carrier. It was estimated that more than 400 liquefied petroleum gas (LPG) carriers could transport ammonia as of 2021 [122]. Globally, ammonia terminals are present at 38 ports that export ammonia and 88 ports that import ammonia, including six ports that both export and import ammonia [123].

Methanol has been shipped and handled for over 100 years, and it has become one of the top five chemical commodities shipped worldwide. Its handling is available through existing terminals in almost 90 of the top 100 ports worldwide [124, 125]. Like ammonia, methanol is ready for immediate use as a feedstock in chemical processes and as a fuel [126-129].

LOHCs can be stored in ports and shipped safely under ambient conditions. Their properties are like crude oil-based liquids; therefore, existing mature oil supply chains can be utilised. Among various organic hydrides, the dibenzyl toluene (DBT) and methylcyclohexane (MCH) are considered inexpensive, high-efficient and high compatibility with conventional petroleum refining, transportation, storage, and distribution [98, 130, 131]. The first small-scale transoceanic H2 shipping via MCH from Brunei to Japan was implemented in 2020 [82]. The major disadvantages of LOHCs are that they cannot be used as energy directly, and the energy demand of endothermal dehydrogenation is on the same level as for H2 liquefaction process.

Based on different technical pathways, the required infrastructure for ports is different. Fig. 7 summarises the port infrastructure required under different H2 forms [132]. For exporting ports, to reduce transportation costs, H2 production plants are generally located near the ports. For example, the H2 hubs funded by the Australian government are all close to the ports [63]. The conversion facilities are generally located near or inside the ports and close to the storage tanks. The transport between production plants and conversion facilities is accomplished by pipelines. The storage tanks and the berths are connected by pipelines. Dedicated loading arms are needed on the berths. For importing ports, after the ships are unloaded, the commodities are generally transported out of the ports by pipelines or road tankers. More than one technical pathway could be chosen in a port; therefore, different infrastructure might be needed, which leads to the complexity of the layouts and challenges of risk management.

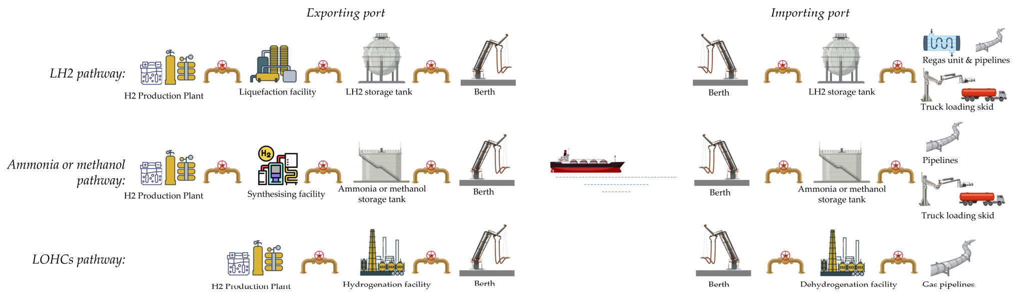


Fig. 7 Hydrogen port infrastructure

3.3 Possible Early Hydrogen Exporting and Importing Ports

Based on the information in section 2, Fig. 8 identifies 11 possible early H2 ports in the three countries. Eight ports are exporting ports including the Ports of Hedland, Darwin, Townsville, Newcastle, Hastings, Geelong, Bonython, and Bell Bay in Australia; and three ports are importing ports including the ports of Kobe and Onahama in Japan and the port of Cromarty Firth in the UK.

Note: the green marks represent the exporting ports; the blue marks represent the importing ports.

Fig. 8 Possible early hydrogen ports in three countries

The involvement of shipping companies is essential to realise the H2 transoceanic trade in practice. Pioneering shipping companies that have been studying or demonstrating the H2 shipping include Mitsui OSK Lines [133], NYK Line [134], and Shell Japan [135].

3.4 Ports' Readiness for Hydrogen Trade

Ports are hubs for the large quantity trade of H2 and its derivatives. They are in the front seats of the shift from fossil-based to carbon-free economy. Therefore, ports should prepare immediately, not only for the H2 trade between ports but also for decarbonising themselves and their adjacent areas. On the one hand, infrastructure building or renovation, terminal operations, risk management should be considered; on the other hand, ports can aggregate the needs of large-scale customers and clusters, such as the heavy industries and transport sector. The various H2 forms have their advantages and disadvantages. Therefore, in the short term, each form has its own suitable application scenarios, and ports may need to be properly prepared for all of them.

3.4.1 Infrastructure

To implement H2 trade on a large scale, it is necessary to develop new infrastructure and/or conduct comprehensive modifications of the existing systems. Among various H2 forms, the port infrastructure building or renovation for ammonia, methanol, and LOHCs is mature technologies. H2 liquefaction technologies are also well-developed [136]. Only large-scale LH2 storage tanks and loading/unloading equipment are still in their infancy [137]. In the world's first LH2 international trade pilot project, the capacity of LH2 tanks in the Port of Kobe is 2,500 m^3. At present, there is no existing reference design for large-scale LH2 storage tanks [138]. It is still challenging to enlarge LH2 tanks due to the immaturity of high-performance thermal insulation technology and welding thick plate materials at the construction site [137, 138]. The high-performance vacuum thermal insulation is needed for loading/unloading arms requiring flexibility and mobility, which also brings about technical challenges. Even though the pilot project has demonstrated the feasibility of the LH2 loading/unloading, many development works are still needed to improve the reliability and reduce costs to make it commercialised.

Currently, H2 infrastructure in ports is gradually moving from concept to reality. The LH2 exporting terminal in the Port of Hastings of Australia and the importing terminal in the Port of Kobe of Japan have been demonstrated. In Australia, in addition to the Port of Hastings, the Port of Townsville is also planning an LH2 exporting project [139]. Green ammonia plants have been planned in the Port of Hedland [70], Bonython [68], Bell Bay [140], and Townsville [139]. Green methanol projects are considered by the Port of Bell Bay [141]. In Japan, Onahama port is planning to import ammonia and LH2, and a 40,000 m^3 ammonia tank and a 50,000 m^3 LH2 tank are being considered [85]. The status of these infrastructures has been benchmarked, which is a basic step towards identifying the technological improvements needed for infrastructure to support the global H2 supply chains. H2 can also be seen as an opportunity for existing oil and gas infrastructure operators. For instance, some energy companies plan to make the liquefied natural gas (LNG) importing terminals H2-ready or ammonia-ready [142, 143].

3.4.2 Risk Consideration

Risk acceptance of H2 port is necessary for enabling conditions for H2 supply chains to become a reality. H2 handling in ports should demonstrate that the safety levels are equivalent to those of the existing cargo handling. It is worth noting that even minor incidents involving H2 handling could significantly affect the development, deployment, and public acceptance of H2 technologies. This subsection identifies risks and their countermeasures for various H2 forms.

(1) Liquid Hydrogen

H2 faces increased public concern about risks due to major accidents, including the Hindenburg disaster in 1937 [144], the Challenger disaster in 1981 [144], and the tank explosion in South Korea in 2019 [145]. LH2 is like LNG in terms of properties to a certain extent; LNG is thus used as a reference to identify risks. Table 3 presents a comparison of the risk-related properties of LH2 and LNG [146, 147].

Tab. 3 Comparison of the properties of liquid hydrogen and liquified natural gas

	LH2	LNG
Boiling point (K)*	20.3	111.6
Liquid density (kg/m^3) *	70.8	422.5
Gas density (kg/m^3) ** (Air: 1.198)	0.084	0.668
Latent heat of vaporisation (J/g) *	448.7	510.4
Lower flammable limit (% volume percentage) ***	4.0	5.3
Upper flammable limit (% volume percentage) ***	75.0	17.0
Lower detonation limit (% volume percentage) ***	18.3	6.3
Upper detonation limit (% volume percentage) ***	59.0	13.5
Minimum ignition energy (mJ)***	0.017	0.274
Auto-ignition temperature (°C)***	585	537
Diffusivity in air (cm^2/s)	0.61	0.16
Critical temperature (K)	33.19	190.55
Critical pressure (kPa)	1,315	4,595
Viscosity (10^{-6} g/cm.s) **	13.49	116.79
Flame temperature in air (°C)	2,396	2,230
Maximum burning speed (m/s)	2.6	0.43

Note:

*: at 101.325kPa.

**: at 20°C and 101.325kPa.

***: air mixture at 25°C and 101.3kPa.

Accordingly, main hazards are summarised as follows [118, 144, 148]:

- Prone to leak
  H2 has low viscosity and high permeability, which makes it not only prone to leak from welds, flanges, and gaskets, but also challenging to be detected and controlled.
- Hydrogen embrittlement
  Due to the high permeability, H2 is easily dissolved in the metal alloy. The hydrogen atoms aggregate into hydrogen molecules in the metal alloy, causing stress concentration, which leads to crack formation and propagation. Generally, high-strength steels, titanium alloys, and aluminum alloys are prone to hydrogen embrittlement. Hydrogen embrittlement is related to the carbon content in metal alloys. Pure unalloyed aluminum has high resistance to hydrogen embrittlement, grade-316 stainless steel and copper-nickel alloy can be used in H2 storage and transportation, and copper can be used in low-pressure equipment [149].
- Flammable and explosive
  The flammable limit range and detonation limit range of H2 are wide, and the minimum ignition energy is low, making H2 extremely flammable. Therefore, places where H2 is stored and handled must not only strictly prohibit hot works, but also take strict anti-static measures. The H2-burning flame is less visible during the day, making it difficult to detect. H2 fires have high combustion rates, which makes the flame hard to put out. There is a high probability of explosion in an enclosed space.
- Cryogenic
  LH2 tanks, piping systems, and equipment are needed to withstand cryogenic temperatures. In addition, the expansion and contraction of materials caused by temperature changes should be highlighted. The temperature of unheated boil-off gas is about -150°C, which might also cause damage to materials. A large amount of LH2 in contact with water may cause the rapid phase change explosion [150].
- Rapid evaporation

The boiling point and latent heat of vapourisation of hydrogen are low, leading to the high evaporation rate. If LH2 is completely vapourised in a fixed volume, the pressure in the volume increases quickly. Therefore, the design of thermal insulation and pressure storage capacity of tanks and pipelines is crucial.

Since LH2 has been used in the aerospace industry for decades, there are numerous publications on risk identification and control. For example, US NASA reviewed LH2 incidents in 1974 [151] and concluded that the number of accidents could have been reduced if the established NASA rules and regulations had been followed. Lowesmith, Hankinson and Chynoweth [152] reviewed LH2 incidents associated with liquefaction, storage, and transport. They revealed that most reported incidents resulted in a release, and about 50% of these releases were ignited. All the ignited releases resulted in either a fire or an explosion. Besides, according to the safety reports on H2 refuelling stations from 2012 to 2017, the overall safety record of the H2 refuelling station is excellent. Hydrogen leaks were minor without accumulation, and generally coincided with the commissioning of new stations, and there were no single subsystem dominated events [153]. Hence, the existing knowledge about LH2 safety is an asset for ports to get ready for LH2 handling.

(2) Ammonia

Ammonia is highly corrosive and toxic which poses specific safety challenges. To deal with corrosion, material selection for equipment needs to follow regulations and standards [154]. Ammonia's toxicity, even at low concentration of 5 parts per million (ppm), creates a perception of it as highly toxic despite the ''immediately dangerous to life or health'' (IDLH) value (300 ppm) and threshold limit (25 ppm) concentrations being much higher [101]. Exposure to toxic ammonia in the air causes burning of the eyes, nose, throat and respiratory tract, and could result in blindness, lung damage or death for humans [155]. Furthermore, ammonia has a serious impact on marine life when spilling into the ocean [104, 156, 157].

Quest [158] stated that handling of anhydrous ammonia is similar to those of gasoline and LPG, and summarised that associated risks are within the accepted criteria. de Vries [159] studied 61 failure modes on a conceptual ammonia-fuelled ship and proposed potential mitigation measures. The study concluded that once proper mitigation measures are put in place, the possibility of a catastrophic failure becomes extremely low. Besides, it was noted that the self-alarming nature of ammonia, due to its strong odour, indicates that leakage could be detected early. Hansson [160] conducted a study to assess the prospects of ammonia as a marine fuel. They concluded that the safety performance of ammonia fuel is at the same level as that of LNG. Ammonia has been handled in ports for decades, therefore, its safety knowledge and know-how have been established.

(3) Methanol

Methanol is toxic to humans through ingestion, inhalation of vapours or skin absorption. If a person ingests 10ml of pure methanol, it will be metabolised into formic acid, which damages the central nervous system and may cause permanent blindness. 30 mL can be fatal, although the median lethal dose is about 100 ml. The toxic effects take hours to start, and an effective antidote can often prevent permanent damage [161]. Methanol does not appear to pose a severe risk to aquatic life. A methanol spill at sea would quickly disperse to non-toxic levels because of wind and wave action [162]. Methanol is corrosive, and its corrosiveness is related to its purity and temperature. Pure methanol is almost non-corrosive to metals below 100°C; fuel methanol is highly corrosive to some metals and plastic products [163]. Therefore, material selection for equipment needs to follow regulations and standards [164]. Methanol has been handled in ports for many years, and experience have been amassed in risk management of the methanol handling.

(4) LOHCs

Both DBT and MCH have certain toxicity, but their toxicity is much less than that of ammonia and methanol, even less than that of diesel. DBT is no risk of explosion or flammability [100]; however, fire and explosion risks of MCH deserve attention. LOHCs are like oils whose risk managements are well-established in ports.

Overall, Table 4 presents the comparison of physical, chemical and risk properties of different hydrogen forms [98, 131, 165, 166].

Tab. 4 Comparison of physical, chemical and risk properties of different hydrogen forms

	H2 (CH2 350bar/CH2 700 bar/LH2)	**Ammonia**	**Methanol**	**LOHC (DBT)**	**LOHC (MCH)**
Composition	H2	NH3	CH3OH	C21H38	C7H14
Molecular weight (g/mol)	2.0	17.0	32.04	290	98.2
Boiling point (°C)	-253.15	-33.15	64.5	353.85	100.85
Density (g/cm3)	0.023/0.042/0.071	0.682	0.792	0.91	0.769
Hydrogen density by volume (kg/m^3)	23/42 /71	121	99	56.4	47.3
Hydrogen density by weight (wt%)	100	17.8	12.1	6.21	6.16
Energy density (MJ/kg)	120	18.6	19.9	/	/
Flash point (°C)	No data	132	12	212	-6
Auto-ignition temperature (°C)	585	630	440	500	283
Flammable limit (vol%)	4.1–74.2	15–28	6-36.5	No data	1.4–6.7
Toxicity (TPI/mg) *	0	No data, but very high	29.7 (Medium)	13.8 (Low)	7.3 (Low)
HMIS® Rating**, Health-Flammability-Physical hazards	1-4-3/1-4-3/3-4-1	3-1-2	1-4-0	3-1-0	1-3-0
NFPA 704 diamond***, Red-Blue-Yellow	4-0-0/4-0-0/4-3-0	1-3-0	3-1-0	1-0-0	3-2-0

Note:

**The toxicity potential indicator (TPI) is given for a range between "0" (substance with no known hazard) and "100" (extremely toxic substance) [165].*

***HMIS® ratings are based on a 0-4 rating scale, with 0 representing minimal hazards or risks, and 4 representing significant hazards or risks [167].*

**** National Fire Protection Association (NFPA) 704 diamond is used by emergency personnel to quickly and easily identify the risks posed by hazardous materials. The four divisions in the diamond are color-coded with red on top indicating flammability, blue on the left indicating level of health hazard, yellow on the right for chemical reactivity, and white containing codes for special hazards. The ratings are based on a 0-4 rating scale, with 0 representing minimal hazards or risks, and 4 representing significant hazards or risks [168].*

3.4.3 Public Acceptance

It is necessary to consider public acceptance when implementing H2 technologies on a large scale. Some scholars have conducted H2 public acceptance studies. For example, within a large-scale H2 infrastructure project, quantitative data on the acceptance was gathered among the German population [169]. The results confirm the positive perception of H2 on a general level. However, the high level of acceptance is decreasing when it comes to infrastructure implementation in the own neighbourhood. The results showed NIMBY (Not in My Back Yard) issue could be addressed through the active participation of residents. A public survey was conducted in March 2015 in Japan asking about public awareness, knowledge, perception, and acceptance regarding H2, H2 infrastructure and fuel cell vehicle [170]. The study found that people have become a little more positive about H2 infrastructure in the baseline but more cautious about the risks and benefits compared with the two previous surveys conducted in 2007 and 2009. A national survey was conducted in Australia in 2018 to evaluate the public's response to H2 domestic use and export [171]. It was concluded that "support for an H2 export industry was influenced by levels of trust in the government to manage the associated risks and the industry's commitment to climate protection."

A study has been conducted to analyse in detail the perspective of experts about ammonia-based technologies through semi-structured interviews [172]. All participants mentioned the 'well-established knowledge' for the handling of ammonia as one of the most positive things. On the other hand, most of the experts mentioned toxicity as the main disadvantage. It was observed that experts are aware of the importance of considering public view at the development stage of new technologies. Interestingly, all their answers reflected that the public should be included, especially in an early stage. After all responses were analysed, it was concluded that for the experts, the public is seen more as a barrier to the development rather than an enabler. It can be seen that efforts are still needed to make H2 and its derivatives better accepted by the public.

3.4.4 Regulation and Standard

Exporting and importing H2 through ports are subject to a range of regulations and standards designed to manage the associated risks. H2 relevant policies are relatively clear; however, regulatory uncertainty and the lack of standards are major barriers to H2 international trade. Safety is seen as a paramount concern in relation to the regulations and standards. While they do not expressly refer to H2, existing safety regulations and standards are arguably broad enough to capture most aspects of the H2 industry. Nevertheless, it would be prudent to adopt them specifically dealing with H2 in ports due to the complexity of layout. This subsection presents the readiness of regulations and standards for H2 and its derivatives in ports.

(1) Australia

Production plants, pipelines, and storage tanks are specialised H2 infrastructure and in Australia they requires different levels of governments' planning and environmental approvals. Generally, existing planning approval regimes would be sufficient to accommodate H2 infrastructure, but the states or territories may consider utilising or creating new streamlined assessment and approval processes to fast-track H2 development [173]. H2 projects may also require environmental licences and permits due to their environmental impacts, including the use or production of dangerous chemicals such as ammonia [174]. In terms of standards, Standards Australia adopted eight key international H2 standards in 2020 [175], including safety standards for the material, design and construction of generators (gas reforming and electrolysis), transportable gas storage devices, land vehicle fuel containers, and refuelling stations. Some states have begun the process of creating their own standards for the H2 production and use [174]. However, tailor-made regulations and standards for ports are still gaps.

(2) Japan

H2 is regulated as a type of high-pressure gas in Japan, therefore,The High-Pressure Gas Safety Act plays a central role [81]. Besides, Fire Services Act should be complied with for H2 infrastructure. Based on the pilot LH2 terminal in the port of Kobe, Japan has been working on increasing the scale of development and international standardisation [137]. For example, chaired by the Japan Ship Technology Research Association, ISO/DIS 24132 Ships and marine technology — Design and testing of marine transfer arms for liquefied H2 has been issued. Despite the progress made so far, significant gaps in regulations and standards for H2 ports remain, particularly concerning the design and arrangement of large-scale tanks.

(3) The UK

In the UK, H2 is under the definition of gas in the Gas Act 1986, it is thus regulated as part of the gas network. In terms of health and safety, the Health and Safety Executive (HSE) requires compliance with the Gas Safety (Management) Regulations 1996, the Pipeline Safety Regulations 1996, the Planning (Hazardous Substances) Regulations 2015, the Control of Major Accident Hazards Regulations 2015, and the Dangerous Substances and Explosive Atmosphere Regulations 2002 [176]. The UK adopted the EU's Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) regulating the road transport of H2 [176]. However, there are currently no specific regulations and standards in place for H2 ports within the country.

3.4.5 Education and Training

The handling of H2 and its derivatives in ports requires special skills and education. Ports, governments, industry bodies, and academia need to work together to spread information and awareness about the safety associated with H2 and its derivatives. Some countries have begun education actions. For example, in Australia, a National Hydrogen Skills and Training Analysis has been conducted to identify and plan for the future skills and training needs of Australians working with H2 in 2022 [177]. Japan has established a personnel training centre for H2. The UK's Health and Safety Executive provides H2 safety training service [178]. However, these training services have yet to cover H2 handlings in ports in a comprehensive manner.

3.5 Ports' Readiness for Hydrogen Application

Currently, most ports' operations depend on fossil fuels, emitting a large amount of GHGs. Up to date, the data on total GHG emissions from ports is not yet available [179]; however, some countries' port emissions have been reported. For example, a total of 548,075 tonnes of CO2 were emitted in five major UK ports in 2008 [180]; about 97,000 CO2 equivalent emissions per year for the port of Osaka in Japan, and about 95,000 tonnes CO2 equivalent emissions per year for the port of Sydney were estimated in 2017 [181]. Japan's ports cover 99.6% of its international trade, and around 60% of overall CO2 emissions come from oil refineries, thermal power plants, iron works, and petrochemical complexes, many of which are in port areas [182]. Some ports have announced their decarbonisation targets. For example, Australia's Pilbara Ports Authority and Japan's Kobe port set their goals to achieve net zero by 2050 [183, 184]. To achieve the decarbonisation targets, the use of H2 is expected to be one of the options for ports. This subsection reviews the status and action plans of utilising H2 in ports in the three countries.

3.5.1 Ports' Actions

In the three countries, some ports have expressed their planned actions on adopting H2 as an energy vector, as presented in Tab. 5. The primary applications of H2 in ports are for mobility and bunkering.

Tab. 5 Ports' planned actions on using hydrogen

Port/Country	Key points	Progress	Ref.
Port of Newcastle / Australia	• To support the development of a H2 economy in the Hunter Region. • The hub will initially install a 40 MW electrolyser and increase to a capacity of over 1 GW.	• The port has launched a $A3 million feasibility study into the development of a green H2 hub that includes the backing of a $A1.5 million funding grant from the Australian Renewable Energy Agency (ARENA). The study includes exploring how the project could be developed and ways in which green H2 could be used. These uses include mobility, bunkering, energy production and other industrial uses, such as the production of green fertiliser.	[185]
Japan's Carbon Neutral Port (CNP) Initiative	• To decarbonise port operations by introducing zero-emission cargo handling equipment, vessels, and trucks. • To decarbonise industries in port areas.	• Studies of utilisation of H2 for port loading/unloading machinery, and stand-alone H2 power sources are undergoing.	[182]
Port of Yokohama/ Japan	• To develop a H2 supply chain in Yokohama's waterfront area.	• The City of Yokohama is examining the potential for the stable supply of affordable H2 via pipelines in Yokohama's waterfront area.	[186]
Port of Kobe/ Japan	• To establish a H2 supply chain system in the port.	• H2 import from Australia has been demonstrated.	[186]
The Port of London Authority (PLA)/ UK	• To develop a UK H2 highway network that consists of land, sea, and ports.	• An analysis has been completed.	[186]
Port of Felixstowe/ UK	• Plans are being developed to use green H2 for onshore purposes, such as road, rail, and industrial use, with the potential to create liquid forms, such as green ammonia or e-methanol.	• ScottishPower, with Hutchison Ports, is exploring the opportunity to develop, build and operate a multi-hundred MW green H2 production facility at the Port of Felixstowe – with the potential to decarbonise industry and transportation in the region.	[187]

3.5.2 Hydrogen Application Cases in Ports

As the H2 fuel cell technology matures, in-port H2-powered vehicles and ships are being tested or demonstrated.

(1) In-port vehicles

In-port operations involve many cargo-handling vehicles, including prime movers, yard trucks, forklifts, container movers, and gantry cranes, typically equipped with fossil fuel-based engines. These vehicles are responsible for a significant fraction of emissions from ports. H2 has the potential to fully replace the fossil fuels used on such as port vehicles. In the three countries, some H2-powered in-port vehicles are being or will be demonstrated, as shown in Tab. 6.

Tab. 6 Demonstration projects of hydrogen-powered in-port vehicles

Port/Country	Description	Ref.
Port of Townsville/ Australia	• Five H2 fuel cell trucks will be used to transport zinc from Sun Metals' Townsville mine to the Port of Townsville to be shipped worldwide.	[188]
Port of Kembla/ Australia	• Two H2-powered prime movers will be demonstrated. • A H2 refuelling facility will be built at Coregas' existing Port Kembla H2 production facility.	[189]
Port of Kobe/ Japan	• A H2 fuel cell powered rubber-tired gantry (RTG) container yard crane will be introduced at Kobe International Container Terminal.	[190]

(2) In-port vessels

Using H2 as a zero-emission fuel for in-port vessels gains more attraction. In the three countries, some H2-powered in-port vessels are being or will be demonstrated, as shown in Tab. 7.

Tab. 7 Demonstration projects of hydrogen-powered in-port vessels

Delivered year/Country	Ship name	Ship type	Proponent	Ref.
Unknown/Australia	Unknown	Ferry (200 passengers)	SeaLink	[191]
2021/Japan	Hydro BINGO	Passenger ship	Fukuyama City	[192]
2024/Japan	Unknown	Tugboat	Tsuneishi	[193]
2012/UK	Hydrogenesis	Passenger ship	Bristol	[194]
2020/UK	MV Shapinsay	Ferry	Orkney Islands Council	[195]
2022/UK	Hydrocat 48	Offshore Crew Transfer Vessel	CMB	[196]

3.5.3 Hydrogen Refuelling in Ports

The availability of H2 refuelling is a crucial factor in the adoption of H2 technology in ports. H2 refuelling systems rely on the storage form of the fuel. Currently, high-pressure H2 refuelling technologies have reached a mature stage and have been successfully implemented in some ports in China [197] and the US [198].

There are two primary sources of H2 in H2 refuelling stations. The first involves centralised H2 production, where H2 is produced centrally and then transported to refuelling stations through trailers and pipelines. The second source involves direct H2 production within the refuelling station itself.

In addition to stationary refuelling stations, there have been successful demonstrations of mobile H2 refuelling trucks. These mobile stations offer flexible and cost-effective solutions for facilitating the use of H2 as a fuel within ports [199].

3.5.4 Standards

The International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO) have established H2 standards that primarily focus on safety and testing

requirements for road vehicles. These standards, listed in Tab. 8, are widely adopted as regulatory components in several countries. However, there is currently an inadequate set of standards to comprehensively address H2 applications in ports.
To address this gap, the ISO Technical Committee 197 has been assigned the responsibility of developing a comprehensive set of international standards for systems and devices used in the H2 value chain [200]. These forthcoming standards aim to cover a wide range of aspects related to H2 applications in ports, ensuring safe and efficient implementation.

Tab. 8 International hydrogen standards

Target	Standard number	Title
Utilisation	IEC 62282 series	Fuel cell technologies
	ISO 14687	Hydrogen fuel quality — Product specification
	ISO 16110 series	Hydrogen generators using fuel processing technologies
Storage	ISO/TR 15916	Basic considerations for the safety of hydrogen systems
	ISO 15399	Gaseous hydrogen — Cylinders and tubes for stationary storage
	ISO 26142	Hydrogen detection apparatus
Refuelling	ISO 17268	Gaseous hydrogen land vehicle refuelling connection devices
	ISO/TS 19880-1	Gaseous hydrogen — Fuelling stations

The International Maritime Organization (IMO) is responsible for developing international regulations regarding the use of H2 on ships. The IMO International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code) specifically addresses H2 as a ship fuel. Currently, the IGF Code working group has finalised an interim guideline for H2 fuel cell installations [201]. The development of requirements for H2 storage and fuel supply systems is the next stage of their work. In addition, the IGF Code allows for the use of alternative risk-based design methods to design H2 storage and fuel supply systems.
Certain classification societies have created their own guidelines for the use of H2 as a marine fuel, as shown in Tab. 9. The publications from these classification societies play a significant role in promoting the adoption of IMO regulations. In cases where a classification society has established a comprehensive set of rules for H2 as a fuel, which address specific requirements not covered by the IMO's regulations, a Flag Administration may accept the application of these rules to facilitate alternative design approaches. Furthermore, the rules developed by classification societies can serve as a foundation for the development of future IMO regulations.

Tab. 9 Classification societies' rules or guidelines

Classification Society	Rules or guidelines	Ref.
ABS	Hydrogen as marine fuel	[202]
BV	NR 547: Fuel cell power systems on board ships	[203]
CCS	Guidelines for Ships Using Alternative Fuels	[204]
DNV	Rules Part 6 Chapter 2 Section 3 Fuel Cell Installations	[205]
KR	Guidance for Fuel Cell Systems on Board of Ships	[206]

3.6 Gap Identification

This section identified the following gaps in H2 trade though ports and H2 applications in ports in Australia, Japan, and the UK.

- Key technologies for building large-scale port LH2 facilities need to be developed.
- Ports' risk management protocols for H2 need to be elaborated, particularly from an international standardisation perspective.

- Effective information and knowledge-sharing platforms need to be established to promote public acceptance of H_2 ports.
- Regulations and standards for ports' H_2 handling and use are expected to be developed.
- Education and training courses are required for H_2 handling and use in ports.
- Refuelling infrastructure is needed for H_2 applications in ports.

4. Interview Findings and Discussion

This section presents the results and discusses findings obtained from interviews with key stakeholders in Australia, Japan, and the UK. It offers a comprehensive understanding of the opportunities and challenges associated with exporting/importing H2 and its derivatives, as well as using H2 as an energy source within ports. Additionally, it provides strategies for overcoming these challenges.

4.1 Interview Objectives

Through interviews, this study aimed to achieve the following objectives in the context of H2 trade and applications.

- Identify the opportunities available to ports and port regions.
- Determine the functions of ports in facilitating international H2 trade, including the infrastructure and superstructure requirements.
- Explore the requirements for efficient, effective, and safe operation in ports that handle H2.
- Evaluate the status of standards related to H2 ports.
- Identify potential challenges and barriers to applying H2 technology in ports and terminals, particularly with regards to logistics.
- Assess the government support required to promote the development of H2 ports.

4.2 Methods

A semi-structured interview method was employed to collect information from key stakeholders of H2 port supply chains [207]. The target interviewees were professionals working for ports, H2 and its derivatives production, export and import, shipping companies, and government agencies. This qualitative interview method promotes two-way communication, enabling interviewers to gain insights into participants' reasoning and thought processes. It allows researchers to explore participants' attitudes, beliefs, and emotions regarding a specific question and to delve deeply into their perspectives.

4.2.1 Interview Guide

To facilitate interviews, an interview guide was created by the researchers. Questions were developed based on the abovementioned objectives with research key words in the following.

- **Opportunities**: the opportunities of H2 trade and application for ports and regions
- **Functions**: the ports' functions in facilitating international H2 trade, including infrastructure and superstructure requirements
- **Operations**: the requirements for efficient, effective, and safe operation in H2 ports
- **Standards**: the status of standards on H2 operations and application in ports
- **Challenges**: potential challenges of H2 logistics in ports and barriers to the application of H2 technology in ports
- **Supports**: supports needed from governments

Tab. 10 presents a detailed overview of the interview guide. The target interviewees were grouped as A, B, C and D, 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. An interview guide with questions was developed for each group but some questions were asked to multiple groups, as shown in Tab. 10.

Tab. 10 Interview guide

Key words	Interview question	Group
Opportunities	(1) Which forms of H2 or its derivates (for example, ammonia, and methanol) are you focusing? What are the potential markets?	A, B
Opportunities	(2) What opportunities will be brought to ports through the involvement in the H2 supply chains?	A, D
Functions	(3) Which port do you plan to use for exporting and importing H2 and its derivates? What functions can the port play to help manage your exporting/importing H2 and its derivates?	B
Functions	(4) What infrastructure and facilities are required for ports to facilitate H2 (and its derivates) trade?	A, B, C
Functions	(5) What types of ships can carry H2 and its derivates? Does your company consider investing in ships for carrying H2/ or other derivates?	C
Operations	(6) What operational risks will be in managing H2 and its derivates 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 codes and standards of safe H2 ports. H2 port in this study refers to managing H2 logistics and applying H2 technology to power port assets. a. Are there standard gaps in H2 and its derivatives operation and application? b. What should be the key codes and standards for a safe H2 port? c. Do you consider developing specific risk management protocols for H2 and its derivatives? d. Do you think there should be a global standard of safety codes for integrating ports into global H2 supply chains? What should be standardised? e. What actions should government agencies (national and international) undertake to ensure a safe H2 port?	A, B, C, D
Challenges	(9) What are the major challenges to ports in managing the export/import of H2 and its derivates?	A, B, C
Challenges	(10) Do you consider applying H2 technology 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 H2 supply infrastructures? For example, H2 refuelling stations. Do you consider providing H2-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 H2 and its derivates on board?	C
Challenges	(13) What are the biggest challenges to shipping and ports in the global H2 supply chain?	C
Challenges	(14) What are your region's key challenges to developing an H2 port (i.e., managing H2 logistics and applying H2 technology to power port assets)?	D
Supports	(15) What kind of support should government agencies provide for the operation and application of H2 or its derivates 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 H2 or its derivates at ports? How do you coordinate and collaborate with key stakeholders to develop H2 ports?	D

4.2.2 Participants

As the H2 industry development has just started, and international H2 trade and its application in the maritime sector is an emerging field of research. To recruit participants with such knowledge and expertise for interview, this research employed a purposive sampling approach to gain representative samples. Such a sampling strategy enables the researchers to utilise their expertise and familiarity in the research field [208].

Participants involved in this study included shipping companies, port authorities/port operators, H2 producers/exporters and importers, and government agencies. They are key stakeholders within the port focused H2 supply chain. This project identified ports involved in H2 supply chains based on the three countries' H2 plans and strategies (such as H2 hubs, importing H2 ports) and then determined the potential participants from those ports involved.

In Australia, there were six H2 hubs at the time of interview planning that involved six ports and relevant investors in production. The target population was 20, including six port authorities/companies, eight producers, and six government agencies. In Japan, there were six planned H2 ports identified, advised by the research partner in Japan. The target population was 20, including six port authorities/operators, six governments, six importers/producers, and two shipping companies. In the UK, four key ports involved in H2 development were identified. The target population was 12, including four port authorities/operators, four governments, and four importers/producers. Invitations were sent to target participants by research partners in the three countries.

As a result, a total of 27 semi-structured interviews were conducted with one face-to-face and 26 online through Microsoft Teams or Zoom due to the impact of COVID-19 pandemic and distance location of the interviewees. In terms of sector, among the 27 participants, seven from ports, seven from producers/exporters, one producer focusing on domestic use, two importers, one shipping company, and nine government agencies. In terms of country, 13 from Australia (four ports, seven producers and two governments), nine from Japan (six ports/governments, one shipping company and two importers), and five from the UK (two ports, one producer, two governments). Participants were either involved in H2 projects (producers, ports, importers, shipping) or renewable energy policy (governments), and most of their positions were senior managers and above, for example, CEO, COO, H2 project manager, head or director of H2 or renewable energy policy, and chief technical adviser. Of notice is that several participants were of chemical and mechanical engineering background (from producers and ports), and some were in charge of managing or regulating dangerous goods (ports, governments). The demographic information shows the representativeness of the interviewees and the reliability of the data collected. Tab. 11 presents the information on the participants and interview methods.

4.2.3 Ethics Approval

The interviews involved human information. Therefore, an ethics application was submitted to the University of Tasmania Human Research Ethics Committee and approved. The interviewees provided their consent for participation before commencing the interviews.

4.2.4 Analysis

The 27 interviews were conducted from September 2022 to early May 2023. The interview durations were from 30 to 75 minutes. The meetings were recorded and fully transcribed. The total word count for all the transcripts is 145,943, and the average word count per transcript is 5,405.

Content analysis methodology was used to analyse and synthesise the interview transcripts. It is a structured and systematic approach to analysing large amounts of textual data, making analysis more manageable [209]. Content analysis can be used both quantitatively, including frequency counts, correlations, trends, and differences over time, and qualitatively such as identifying themes and elaborating on theories [210]. The interview transcripts were analysed according to the research key words indicated in section 4.2.1, i.e., opportunities, functions, operations, standards, challenges and supports. The analysis results are presented in the next section and are elaborated in categories according to the key words.

Tab. 11 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
P23	The UK (Scotland)	Port	A	Online
P24	The UK (England)	Port	A	Online
P25	The UK (Scotland)	Producer/Exporter	B	Online
P26	The UK (England)	Government	D	Online
P27	The UK (Scotland)	Government	D	Online

Note: In Japan, the port authorities are parts of the government, thus, participant 14-18 were assigned to both Group A and D.

4.3 Results

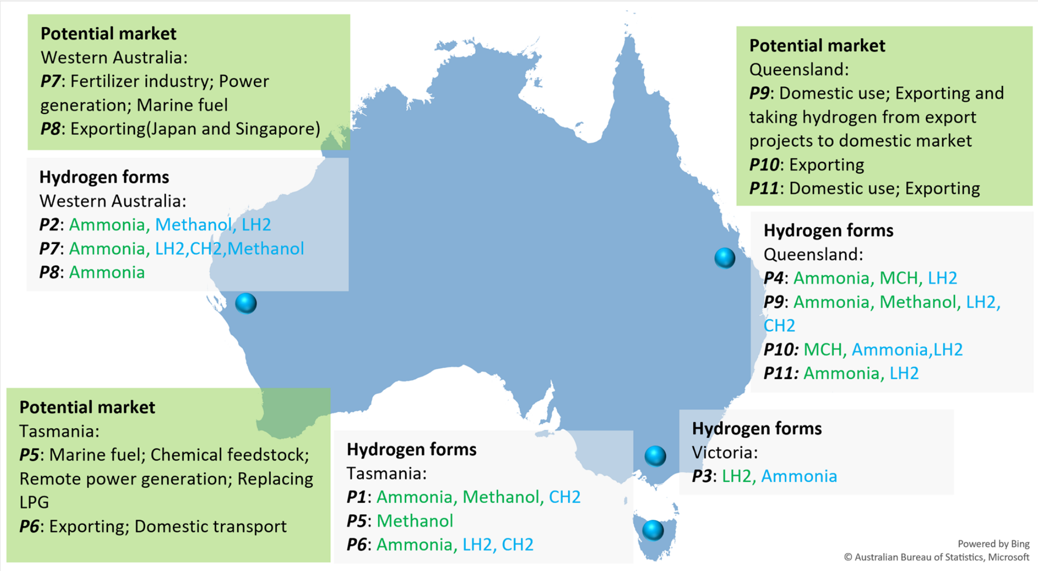
4.3.1 Opportunities

The participants in Groups A (port), B (producer/exporter/importer), and D (government agency) were asked two questions i.e., Question (1) and (2) in Tab.10 relating to H2 forms for trade and potential markets, and opportunities to ports and their regions. The responses to these questions are summarised below with respective country's analysis result.

(1) Hydrogen Forms and Potential Markets

Eighteen participants (eleven from Australia, four from Japan, and three from the UK) indicated the H2 forms they would like to focus on. Additionally, all participants in Group B provided information on their potential markets. Figures 9, 10, and 11 summarise the information for Australia, Japan, and the UK respectively.

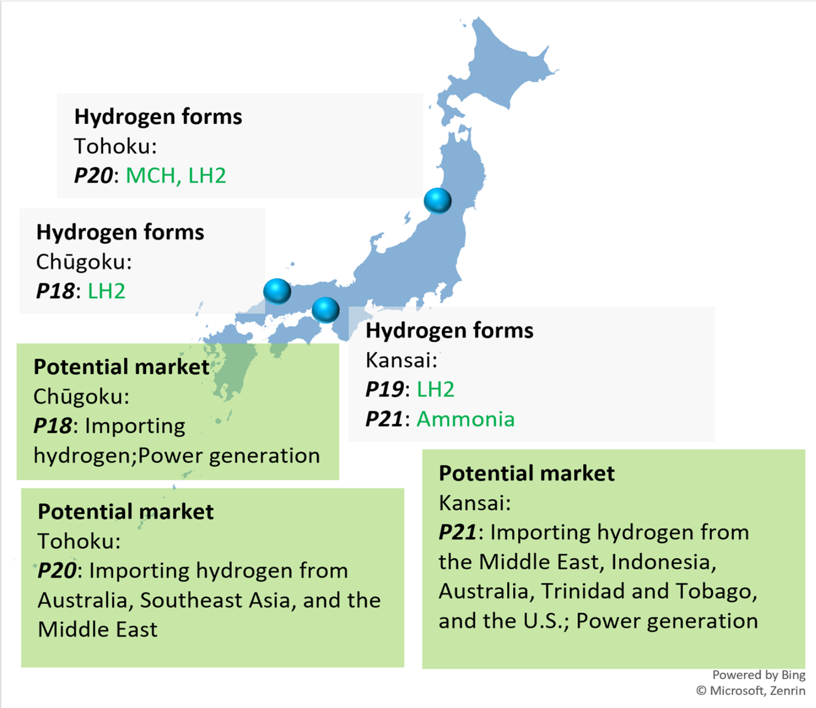
In Australia (see Fig.9), ammonia is the primary focus for participants in the near term, followed by methanol and MCH. However, the participant from Victoria indicated that LH2 is currently a priority due to the ongoing HySTRA pilot project between Australia and Japan, which involved the transportation of LH2. Regarding the potential market, various H2 producers held different expectations. Nevertheless, all participants anticipated Australia will be a major country exporting H2 (or its derivatives) to other countries. The participants also highlighted domestic usage options, including fertiliser, power generation, and marine fuel industries. Notably, P9 mentioned the possibility of utilising H2 from Australian export projects for the domestic market in the long term.



Note: Green fonts indicate the near-term focus, while blue fonts indicate the long-term focus

Fig. 9 Hydrogen forms and potential markets for Australia

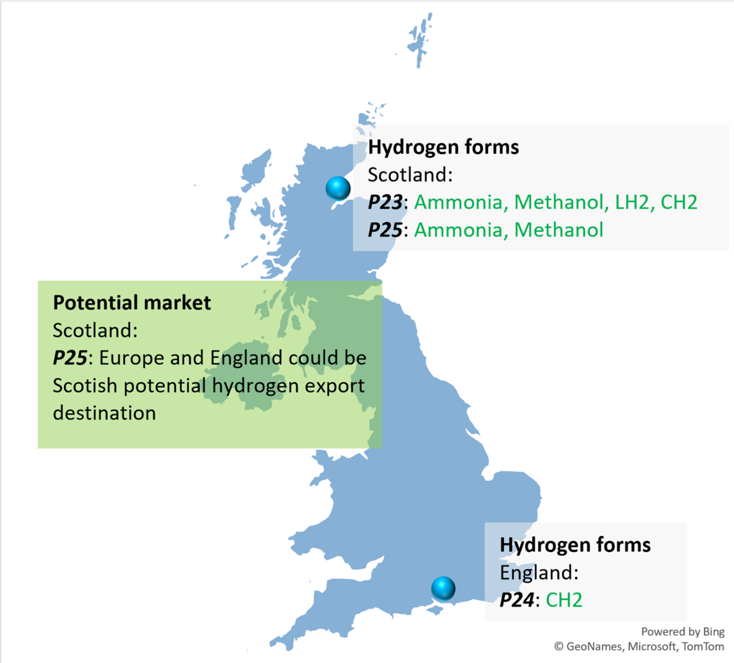
Japan will be the major importer of H2 and its derivatives. Under the national H2 strategy [38], the country placed a particular focus on MCH, LH2, and ammonia as the forms of H2. The participants suggested that importing H2 from other countries would be the initial step, followed by a potential expansion into power generation as a significant market for H2 utilisation (Fig.10).



Note: Green fonts indicate the near-term focus

Fig. 10 Hydrogen forms and potential markets for Japan

The participants from the UK did not clearly express their preference for a specific form of H2. For instance, when P23 was asked, he responded that "any form could be possible." P25 responded "probably ammonia and methanol." On the other hand, when discussing the potential market for H2, P25 suggested that Scotland could become an H2 exporter through ports, given the numerous renewable energy projects (e.g., offshore wind) that had been invested in the country. P25 also mentioned that England and European countries would be the primary targets for Scottish H2 exports (Fig.11).



Note: Green fonts indicate the near-term focus

Fig. 11 Hydrogen forms and potential markets for the UK

(2) Opportunities for Ports and Regions

A total of 15 participants in Group A and D provided their insights on the opportunities of integrating H2 into the economy for ports and regions. The responses are summarised in Tab. 12. Because of the distinct attributes of the three countries, the insights offered by participants from each country possess unique characteristics. From the port perspective, the participants from Australian ports believed that the opportunity for H2 energy lay mainly in exports, and ports could play a role in connecting supply chains. It is worth mentioning that the P2 pointed out that to prepare for exporting H2, the port's primary task is to import renewable energy infrastructure and equipment such as solar panels, wind turbine blades, and nacelles. Therefore, there is a fundamental mindset change in this respect. The Japanese ports focused on strengthening the functionality of importing H2 energy and cultivating public awareness of a H2 society. British ports emphasised the resilience of ports to meet future energy transition demands. Of course, the participants from ports in all countries believed that the use of H2 energy for decarbonisation by ports themselves is an opportunity. From the government's perspective, Australia has opportunities to become a leader in H2 exports, decarbonise hard-to-abate sectors, provide clean energy for business transition, and boost H2 technologies. Japan has opportunities to become a H2 society and benefit its port cities. The UK aims to capture future fuel market share and transition from oil and gas to H2 as the primary energy source for the country.

Tab. 12 Information for opportunities

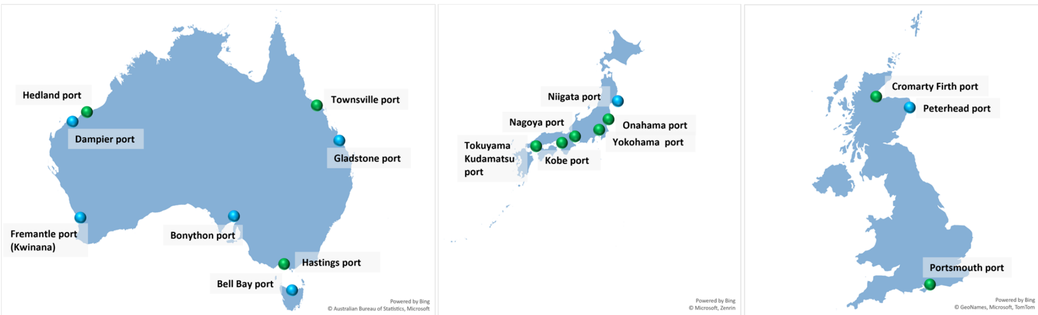
	Port	Region
Australia	• Becoming a major exporter of renewable fuels. • Becoming a renewable energy infrastructure importer. • Growing regional ports (most of the renewable energy projects are in regional areas). • Providing a backbone for producers. • Adding volume to ports' trade. • Decarbonising ports' activities.	• Becoming a H2 export leader • Decarbonising the hard-to-abate industries such as transport, agriculture, mining, and metallurgy. • Providing alternative fuels to help business transition. • Boosting the H2 technology development.
Japan	• 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, resulting in an increase in freight volume for the port.	• Becoming a H2 society leader. • Benefiting the businesses of the port city. • Decarbonising power plants in the port areas.
The UK	• Increasing the port's resilience to future energy demands. • Providing a greater mix of energies for ports and ports' customers.	• Capturing future fuel market share. • Enabling energy transition from oil and gas to H2 in the country

4.3.2 Functions

The participants in Groups A (port), B (producer/exporter/importer), and C (shipping company) were asked three function-related questions (Q3-5) in Tab. 10. The responses to these questions are summarised in the following.

(1) Potential Hydrogen Exporting/Importing Ports

The participants in Group B were asked to identify potential ports for exporting or importing H2. Out of the ten respondents, nine participants, including seven from Australia, one from Japan the UK respectively, answered the question clearly. Based on their responses, the possible ports for H2 exporting or importing were five ports in Australia, one in Japan, and one in the UK. Also, the participants in Group A described their ports' potential for H2. Combining the responses from both Group B and Group A, Fig. 12 illustrates seventeen potential H2 ports, including eight ports in Australia, six in Japan, and three in the UK.



Note: Blue dots representing the ports identified by Group B, Green dots representing the ports described by Group A

Fig. 12 Identified potential hydrogen ports

(2) Port Infrastructure and Facilities

New port infrastructure and facilities are required to support H2 and its derivatives trade, and existing infrastructure needs to be retrofitted to accommodate them. For instance, as mentioned by P1, the properties of H2 and ammonia differ significantly from those of petroleum cargo typically handled in ports. Consequently, careful consideration needs to be given to the design of tanks and pipelines, considering exclusion zones. From a safety perspective, existing port accommodation buildings should be reassessed and retrofitted accordingly.

All participants from Groups A, B, and C responded to the questions regarding infrastructure and facilities. The required infrastructure and facilities for ports are summarised below:

- Process plants (for instance, liquification plants, regasification plants, hydrogenation plants, and dehydrogenation plants)
- Storage tanks
- Pipelines
- Berths
- Loading/unloading equipment
- Powerlines
- Road
- Refuelling stations
- Bunkering vessels
- Security systems
- Safety systems

The infrastructure and facilities mentioned above may not be required by all ports, as their necessity depends on the form of H2 being handled, export or import, and ports' willingness to use H2 or its derivatives as an energy source for decarbonisation.

(3) Ships

During the interview, only one participant (P22) from the shipping company was available to provide insights on H2 shipping, as it was still in the early stage. Fortunately, several participants from different ports or producers, such as P1, P3, P8, P10, and P20, also shared their perspectives on the topic.

According to the participants, the transportation of ammonia and methanol via chemical tankers had been in practice for decades, and the current shipping fleet could be used to transport future H2-based ammonia and methanol. MCH can be transported using chemical tankers. However, in terms of the scale of ships, since MCH has not yet been widely accepted socially, it could be transported by ships with a capacity of thousands of tonnes compared with toluene shipping. As for LH2 and CH2 shipping, new ship designs are required. Although the world's first LH2 carrier was tested in the HySTRA project, building LH2 ships still poses several challenges, such as managing boil-off gas and reducing boil-off rates. On the other hand, CH2 ships could only be utilised for short routes due to their low density, leading to low shipping efficiency. The primary challenge with CH2 ships is high pressure.

Regarding investing in a new shipping fleet, P22 stated that their company was exploring the possibility of building vessels in the future. At the initial stage, one solution that they were focusing on for shipping H2 and its derivatives (such as ammonia and MCH) was the use of ISO tank containers, which provide door-to-door service and are widely available. P11 also expressed ISO tank containers might be used for MCH shipping at the initial stage. P20 expected that ammonia and LH2 could be shipped on a scale comparable to existing LNG carriers.

4.3.3 Operations

The researchers asked participants from Groups A (port), B (producer/exporter/importer), and C (shipping company) about the operational risks of H2 in ports. Specifically, participants from Groups A and C were asked about their training and education needs. Below two subsections are the findings.

(1) Hydrogen-related Operational Risks

Since H2 is a new commodity for ports, it is essential to establish a comprehensive risk management system from scratch. As ammonia and methanol had been operated in ports for decades, some participants believed that the risks associated with them were not a problem. However, most participants acknowledged that while these commodities had been transported for many years in the fertiliser industry or as a chemical feedstock, they had not been handled as larger-scale energy commodities. As a result, there was a lack of accumulated experience in risk management. Although existing knowledge could be helpful, more is needed to address the unique challenges.

Tab. 13 summarises H2 and its derivative associated operational risks that the participants described. To reduce operational risks, the participants put forward some valuable suggestions. P3 and P13 suggested that safety authorities should play a crucial role. Although the shoreside safety administration and the maritime safety authority have their clear working scope, they share the same safety philosophy and should collaborate. For example, in Australia, WorkSafe, state safety authorities, and the Australian Maritime Safety Authority (AMSA) collaborate to ensure ports' safety. Further cooperation between them is necessary, especially in upcoming H2 ports. P4 suggested the quantitative risk assessment could help set high-level risk mitigation plans such as safety distance and blast prevention wall layout. P7 highlighted the significance of establishing a process safety culture as a fundamental approach to manage operational risks in ports. This culture represents a mindset that takes time to develop.

Tab. 13 Operational risks in ports

Cause	Effect	Potential impact
Insufficient risk assessment	• Inadequate risk mitigation measures (safety zone, firefighting capacity, blast wall, etc.)	• Life loss • Asset loss
Insufficient safety prevention	• Gas detection failure • Shutdown system failure	• Leak/Spill deterioration
Inadequate emergency response	• Un available firefighting • Insufficient medical rescue resources	• Life loss • Asset loss
Inadequate cargo/passenger operation protocol	• Improper concurrent operations	• Loss of containment • Potential chemical reactions
Inadequate security protocol	• Sabotage • Accidental mishap	• Loss of containment
Leak/Spill	• Fire and explosion (H2, ammonia) • Toxicity (ammonia, methanol, MCH) • Cryogenic damage (LH2)	• Large exclusion zone • Human life or marine life loss • Marine environmental damage

(2) Training and Education

There is a significant gap in training and education for H2 ports. For example, P13 mentioned the availability of some H2-related training programs in the market. These programs typically focus on basic knowledge. Unfortunately, there was a shortage of experienced personnel to provide training in real-world operations. During the interviews, many participants expressed the need for more comprehensive training and education opportunities. In this regard, governments can play a crucial role. For instance, P7 stated that they received government funding to establish training programs for the port.

According to the participants, the comprehensive training should include the below aspects:

- Safety and health
- Materials and equipment
- Cargo operations
- Cause and effect of incidents/accidents

- Emergency response

4.3.4 Standards

All the participants responded to the question regarding standards and codes. 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 IEC standards. However, it is worth noting that most existing standards are primarily suitable for industrial use and not for using H2 and its derivatives as energy sources. Consequently, there is a significant gap in standards and codes for ports. To ensure the efficient handling of H2, standardisation is necessary for the storage, pipelines, in-port transportation (by road or rail), and loading/unloading processes at H2 ports. Additionally, the certification standards for the cleanliness of H2 and its derivatives are required.

A total of 23 participants provided their expectations in terms of standards, either international or local. As shown in Fig. 13, seventeen (74%) out of the 23 participants expressed a preference for international standards, while three (13%) favoured local standards. Three participants (13%) indicated that their preference depended on the shipping routes and ports involved.

Obviously, most of the participants supported international standards for ports. Australian participants P7 stated that operating the same cargo in the importing and exporting ports should follow the same standards, and P12 also emphasised that international standards could be adopted in Australia. However, others, like P13, were in favour of local standards. They argued that each port has its unique characteristics, and high-level safety or environmental principles could be consistent across all ports, but the operations should be adjusted according to each port's unique features. A Japanese participant P22 suggested that local standards should be used unless international consistency in procedures is established. P10 from Australia and P26 and P27 from the UK argued that adopting local or international standards depended on the shipping routes. For instance, if H2 shipping is only within Europe, following the EU standards would be enough.

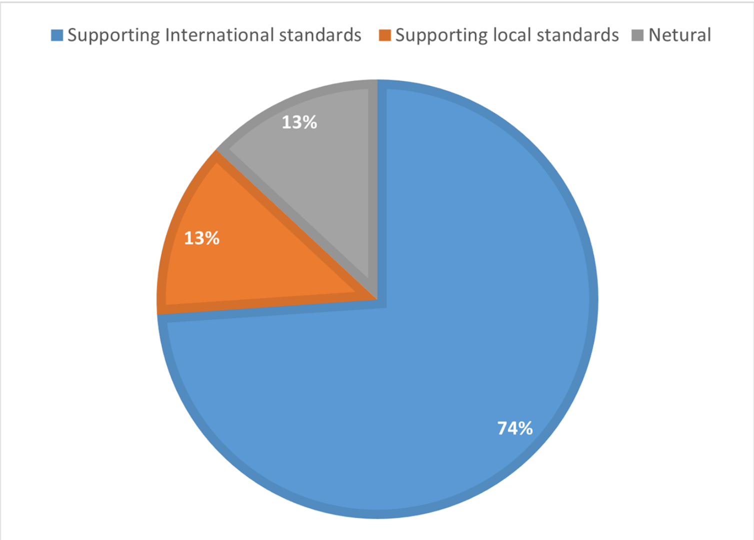


Fig. 13 Responses regarding standard expectations

Governments could accelerate the standardisation process, and some have already taken steps to do so. As stated by P1 and P4, the Australian Standards Committee is currently examining the standardisation of H2. State governments are also developing standards ranging from green certification to safety, either by adopting international standards or drafting local ones. Additionally, P15 and P17 highlighted that the Japanese government and enterprises were actively involved in developing ISO standards, particularly those related to LH2.

4.3.5 Challenges

Six questions (Q9-14) in Tab. 10 were asked to participants of Groups A, B, C and D in relation to the challenges to ports in handling H2 and its derivatives for trade and application of H2 technology in ports. The analysis results reveal four aspects of challenges i.e., port development, H2 application in ports, H2 refulling and bunkering, and shipping.

(1) Port Development

Eighteen out of 27 participants expressed their concerns on the challenges in relation to port development. The first major challenge to the development of H2 ports is land use. Eight participants (P1, P2, P4, P5, P12, P13, P26, and P27) highlighted that the availability of land space was a significant obstacle to overcome. Large land space is needed for renewable power generation (such as solar or wind farms), H2 production (water electrolyser layout), in-port infrastructure building or upgrading, and port safety zone layout upgrading. Ports were struggling to acquire enough land owned by the government or private entities.

The second major challenge lies in the uncertainty of H2 demand, which is the primary concern for participants from importing ports (P14, P15, P16, and P17). While there were optimistic predictions about future H2 demand, ports hesitated to invest without secure selling agreements or contracts. The actual demand is contingent upon the government's strong commitment to decarbonisation and the pricing of H2 and its derivatives. "It will be difficult for private companies to go ahead," as P14 responded. P15 suggested "The burden should be divided equally between government and the private sectors." This presents "a chicken-and-egg dilemma," as P26 described, as scaling up investment could reduce the cost in the H2 supply chains and accelerate technological advancements that help further cut costs. This challenge to importing ports may also pose an obstacle in developing exporting ports, as highlighted by P1.

The third major challenge is the lack of adequate infrastructure. Building new infrastructure is necessary to handle H2, and even existing infrastructure for ammonia and methanol needs to be scaled up for upcoming larger-scale international trade. However, there are limitations to the technology available for building large H2 storage infrastructure, for example, the large LH2 tanks, as mentioned by P2. Additionally, there is a gap in standardisation of infrastructure construction, as outlined in section 3.4. With the entry of many small H2 producers and exporters into the market, P2 suggested that common-use infrastructure should be considered by some ports, in contrast to the current LNG or LPG dedicated infrastructure. However, P7 raised concerns about the difficulty of assessing and certifying the carbon intensity of the cargo from different producers in the same tank if common-use facilities were used. Furthermore, P3 posed the question of how to deal with retiring oil and gas infrastructure with the phasing out of fossil fuels. Were they able to be repurposed for H2 and its derivatives? This issue requires further research to be addressed.

The fourth major challenge is insufficient education. P12 emphasised that education about H2 was not only necessary for port operators but also for government regulators and policymakers. Additionally, providing education on advancements in H2 technology could increase investor confidence in the development of ports, as noted by P16. This challenge was also identified in subsection 3.3.2.

The fifth major challenge is obtaining the social license for H2 ports. As some ports are situated in densely populated areas, the possibility of H2 or its derivatives, particularly the toxic ammonia, being released that causes harm to nearby residents is a significant concern. Also, the potential environmental damage resulting from ammonia leakage is a considerable fear. Therefore, more extensive risk and environmental assessments must be conducted and publicised to build public confidence. This concern was highlighted in interviews by P1, P2, P9, and P18.

Other challenges in H2 ports' development mentioned by interviewees include:

- Availability of resources for H2 production, including upgrading the power grid and securing a sufficient supply of fresh water or desalinated seawater, suggested by P1, P5, and P27.
- The need for openness and information sharing, particularly for government-owned or subsidised projects, as P1 suggested.
- Other issues in H2 Supply chain such as the lack of established "last mile" delivery infrastructure and regulations for road transport of liquid H2, as P19 indicated. In addition, there is currently no maritime legal system for transporting H2 using barges or small tankers.

(2) Hydrogen Applications in Ports

Six participants from Group A (port) provided their views on using H2 as an energy source in ports. Australian participants P1 and P2 identified themselves as landlords and stated that they did not handle energy-consuming equipment or vehicles in ports, so they could not comment on their use of H2 as an energy source. However, they did mention that they were collaborating with port customers, users, and service providers to explore the use of H2 in the future. P3 and P4 expressed their commitment to powering the ports with renewable energy but had not yet decided on whether to use batteries or H2 as their energy source. UK participant P24 stated that it was too early to decide on the use of H2 in ports and would depend on the availability of refuelling infrastructure in the future. Another UK participant P23 acknowledged that H2-based alternative fuels could be used if electrical energy from the grid could not provide the necessary volume of energy needed to service customers. He further noted that H2 could help to decarbonise port operations, reduce emissions, and improve air quality in the port and city. However, some barriers needed to be addressed, including lack of regulatory support, and slow payback for the upfront costs associated with de-risking this type of energy.

(3) Hydrogen Refuelling and Bunkering

Providing H2 fuel services could be an opportunity for ports [211-214]. Interview participants P1, P3, and P4 from Australian ports, as well as P23 from a UK port stated that they were exploring the possibility of building H2 refuelling stations within their ports to cater for potential H2-fuelled vehicles. P24 mentioned that their port was considering the necessary infrastructure for methanol as a “drop-in” replacement fuel for existing port equipment in the short to medium term to reduce carbon emissions, with the potential for H2 storage and use as commercial uptake increases.

Regarding maritime fuel bunkering, P1 said the port would not provide such service as it was not a bunkering hub. P2 stated that the port was considering ammonia bunkering services. The other interviewees P3, P4, P23, and P24 stated they were closely looking at the pathways of the shipping industry’s decarbonisation. Once the industry locked down on the future fuel type and if the fuels were produced within the region, they would consider how to bunker up vessels accordingly.

In summary, the challenges faced by ports regarding the provision of H2 refuelling and bunkering mainly stem from the uncertainty in the downstream H2 application market, making it difficult for ports to make decisions. Paradoxically, the availability of refuelling and bunkering infrastructure serves as an essential prerequisite for catalysing the growth of the downstream market. This is the “chicken and egg” dilemma.

(4) Shipping

The shipping of H2 is still in its early stages, and there were limited interview candidates from shipping companies, considering their involvement in H2 at the time for interview planning. As a result, the research team was only able to interview one expert (P22) from a Japanese shipping company that has been active in exploring H2 and its derivative as marine fuel. P22 provided views on H2 transportation and using H2 as a maritime fuel below.

In terms of H2 transportation, existing chemical tankers can be used if H2 is in the form of ammonia or MCH. Ammonia transport is expected to shift from midsize gas carriers to Very Large Gas Carriers (VLGC). However, the existing ammonia receiving ports are not large enough to accommodate VLGC, so it is necessary to renovate and develop berths to accept these larger ships. When it comes to CH2 or LH2, technical demonstrations are required to determine the feasibility of using these forms of H2 for maritime transport.

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.

4.3.6 Government Support

The participants from different countries expected different kinds of support they needed for developing H2 ports. Therefore, this section presents the analysis result of government support in terms of country.

(1) Australia

Interview results reveal that several key supports from the governments could be considered for successfully developing H2 ports in Australia. Firstly, policies, frameworks, and regulations are necessary for H2 production, green certifications, and operational procedures. P1, P2 and P3 all highlighted this aspect. For example, P1 suggested that this would accelerate the development of premium Australian H2 products for the global market.

Secondly, financial support is crucial. Both direct and indirect funding options should be explored. While some direct funding had been granted to ports by the Australian government, more were needed, as P6 pointed out. P1 suggested that the funding should be directed towards infrastructure development, while P8 emphasised that a significant injection of capital from the government was required to support private companies. 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. P5 highlighted that the US had issued the Inflation Reduction Act (IRA) [215], which subsidises H2 production and made American H2 cheaper than Australia's. To maintain competitiveness, the Australian government should consider similar actions. P7 suggested that carbon tax mechanisms could be used as incentives, such as reducing port fees, rather than a penalty, to encourage low-carbon intensity technologies. P11 recommended the government to put efforts on creating domestic H2 consumption to expand the supply chain.

Thirdly, a constant review of H2 strategies is necessary. While most Australian state and territory governments had H2 strategies and policies in place, they must be reviewed regularly to keep up with the pace of H2 development and competition, as suggested by P4.

Fourthly, government departments should work together to promote efficient port development. Collaboration between departments responsible for electricity, water resources, renewable energy, and infrastructure can foster a shared commitment.

Finally, Australia should play an essential role in inter-government organisations to support the development of a seamless H2 supply chain. P2 emphasised the importance of working in an international environment for the government and recommended that the Australian government enhance its role in inter-government organisations such as the IMO.

(2) Japan

The Japanese government has established several initiatives and funds to promote the development of H2 ports, including the Carbon Neutral Port (CNP) Initiative [182], the New Energy and Industrial Technology Development Organization (NEDO) [216], the METI (Ministry of Economy, Trade and Industry) Green Transformation (GX) league project [217], and the METI Green Innovation Fund project [218]. These initiatives and funds provided policy and financial assistance for port development to accommodate the trade of H2 and its derivatives. For instance, P14 stated that a subsidy of 50% of the cost of extending the quay for H2 importation was available, and P17 mentioned that the GX was a 120 trillion-yen fund supporting carbon-neutral research.

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 CO2 reduction measures. Additionally, P19 and P22 suggested that regulations and tax incentives similar to those in Australia should be implemented to encourage further progress. In Japan, it is important to continue to evaluate and improve government support for H2 port development to accelerate the transition to a carbon-neutral future.

(3) The UK

Effective actions are needed to support H2 infrastructure development in UK ports through dedicated funding, policy frameworks, and regulations. According to P25, P26 and P27, despite the UK government's allocation of funds for H2 projects, specific funding had yet to be designated for ports. The Industrial Energy Transition Fund [219] and Clean Maritime Demonstration Competition Fund [220] provided limited port development support. The £100 million Green Hydrogen Fund, intended to support H2 production projects, provided insufficient support for ports. P24 provided recommendations for the government, including providing adequate funding for H2 infrastructure construction in ports, offering incentives for ports and vessel owners to provide and use H2, and working with regulatory bodies to develop safe and practical toolkits that enable ports of all sizes to transition to H2 and its derivatives. P26 suggested that the HSE (Health and Safety Executive) and MCA (Maritime and Coastguard Agency) could play a proactive role in developing regulations for ports.

4.4 Discussion

Based on the interview results, it is evident that stakeholders recognised the critical role ports play in H2 supply chains. However, actions to overcome the challenges have yet to be actively developed or implemented, resulting in slow progress in the development of H2 ports. If this trend continues, ports may become bottlenecks in the H2 supply chain. In this context, this section discusses potential solutions to expediting the development of H2 ports from the aspects of knowledge, incentive, resource, culture, and safety.

4.4.1 Knowledge

H2 is a novel concept for most port workers but its knowledge will be a significant factor contributing to the development of H2 ports. While people may possess theoretical knowledge, they often lack practical experience. To address this, ports across different nations could establish a platform for knowledge and information sharing to enhance the overall knowledge base of the industry. Some countries have set up H2 education systems [221-223]; however, some early movers may attempt to keep their acquired experience confidential to maintain a competitive edge that can be short-sighted. To ensure a rapid expansion of the H2 market and achieve the goal of promoting economic development while reducing carbon emissions, it is vital to raise the level of H2 knowledge for all stakeholders. One possible strategy is to build a H2 energy knowledge-sharing platform based on the existing global port cooperation organisations (e.g., International Associations of Ports and Harbours, IAPH), through which ports commit to openness and transparency and are dedicated to facilitating the rapid energy transition. Especially for the ports owned or subsidised by the government should play an active role.

4.4.2 Incentive

The carrot-and-stick incentive mechanism for promoting H2 ports may be an effective solution. On the one hand, governments can provide H2 ports incentives for investment and tax reduction, such as funding subsidies, tax exemptions. On the other hand, an increase in carbon taxes can be imposed on ports using fossil fuel. Additionally, government policies should encourage ports to transform into clean energy transmitters and users. In this regard, Japan's experience can be used as a reference. Their first H2 port received financial support from the government and was developed under the Carbon Neutral Port Initiative.

The incentive mechanism for creating H2 demand markets is also essential [224] for developing H2 ports, considering the challenge of demand uncertainty from the interview finding. Regardless of exporting, importing, or port decarbonisation, establishing a H2 demand market requires strong incentive measures [225]. In the early stages of H2 energy applications, the economic disadvantage relative to fossil energy needs to be compensated by incentive measures such as subsidies and tax reductions. In the long term, after the formation of a large-scale H2 energy system, it has great potential to surpass fossil energy in terms of economics and energy supply security. When demands for H2 increase, ports may benefit more from trade.

4.4.3 Resource

For H2 trading facilitated by ports, H2 production and utilisation generally occur near or within the port. H2 production through water electrolysis requires access to land resources, renewable energy-based power generation, and water resources [226]. The participants in this research expressed concerns about the availability of and accessibility to these resources, even in regions with abundant land or water resources. This is because of barriers related to land rights near ports and priority of using water, which hinder the realisation of H2 ports. The strategy of strengthening communication and negotiation among all stakeholders would help to achieve a win-win situation in social and economic benefits and facilitate the transformation of H2 ports.

4.4.4 Culture

In the era of fossil fuels, people focused mainly on economic development, ignoring its environmental harm. However, in the era of renewable energy, equal importance to economic development and the environment should be given. With the development of H2 ports, working culture in ports will change, aligning with the global goal of decarbonisation. During the initial development stage of H2 ports, there may be some economic pain points, but people's awareness of cultural transformation can help recognise this difficulty and contribute to forming a joint effort to overcome it. Once the H2 energy industry has formed a scale, economic benefits will undoubtedly be highlighted, achieving a win-win situation for the economy and the environment.

4.4.5 Safety

Due to H2's safety characteristics, its operation and use at ports differ greatly from traditional fossil fuels. H2's easy leakage and combustibility pose new challenges to port safety [227]. H2 has a history of application in the aerospace industry for decades, and ports could learn from the aerospace industry's risk management experience and establish a new risk management philosophy to guide ports' H2 handling. In addition to the quantitative risk assessment applied to traditional fossil fuel ports, ports can expand their thinking to improve the level of H2 risk management using mature methods applied in the aerospace industry. For example, NASA's Safety Standard for Hydrogen and Hydrogen Systems could be a valuable reference for H2 ports [148]. When people have confidence in the safety of H2, social acceptance will be more easily obtained.

5. Survey Findings and Discussion

The qualitative semi-structured interview results identified opportunities and challenges faced by potential H2 ports in Australia, Japan, and the UK. To further explore the readiness of ports for upcoming H2 trade and applications and assess the general operational risks associated with handling and using H2 in ports, the research team conducted a questionnaire survey. This section presents the findings of the survey.

5.1 Survey Objectives

The objectives of this survey were to:

- Confirm infrastructure and facilities required for an H2 port.
- Identify critical factors for a safe, efficient and effective H2 port.
- Assess operational risks in an H2 port.

This online survey seeks to provide a quantitative understanding of the status of ports' infrastructure and facilities for H2 handling and utilisations, as well as to gather participants' perceptions of the risks associated with H2 operations in ports in Australia, Japan, and the UK.

5.2 Methods

The study employed an online survey method using closed-ended structured questions. This method has the advantage of eliciting quick and accurate responses while minimising participant thinking time [228]. The survey form included closed-ended structured questions including single-answer, multiple-answer, scaled, and ranking questions. Details of the research method are explained below.

5.2.1 Survey Tool

To minimise system errors during data collection, it is crucial to select a well-recognised and stable online questionnaire software. This study compared SurveyMonkey and Microsoft Forms and selected Microsoft Forms for two reasons. Firstly, it offers an app, making it easier for potential participants to respond though personal computers or mobile phones. Secondly, it provides the function of real-time data visualisation, allowing investigators to visualise the progress of data collection in real-time.

5.2.2 Questionnaire

A closed-ended structured questionnaire was developed based on literature review and interview outcomes and made available to potential participants through online access with the Microsoft Forms software. The questionnaire includes the following sections with relevant questions:

- Section A: Demographics including four variables (country, professional field, professional role, and service years).
- Section B: Questions about H2 forms for trade and utilisations.
- Section C: Infrastructure sufficiency for a H2 port.
- Section D: Berth utilisation in a port.
- Section E: Readiness levels of critical factors for an efficient and effective H2 port.
- Section F: Operational risks associated with H2 in ports.

5.2.3 Sample

As H2 trade through ports and applications in ports are emerging fields, the criterion for selecting participants was set to have H2-related knowledge or experience. A purposive sampling approach was therefore applied to obtain representative samples [229]. This sampling strategy allows the researchers to utilise their expertise and familiarity in this research field to target appropriate participants for the survey. As the survey was to investigate port readiness for H2 trade and application and assess operation risks, potential participants included port operators/authorities/companies and H2 producers/exporters and importers as they have knowledge in ports when managing H2 trade and application. This study invited those potential participants involved in H2 projects announced by the governments in Australia, Japan, and the UK for completing the survey. The research team distributed the online survey questionnaire to about 65 potential participants i.e., ports, producers, and importers (Australia 34, Japan 10, and UK 21) through emails and LinkedIn.

5.2.4 Likert Scale

This study employed a Likert scale to gauge participants' opinions on the infrastructure sufficiency levels and readiness levels of critical factors for efficient and effective H2 ports. When developing a Likert scale, it is crucial to specify the number of points on the scale. A nine-point Likert scale was used to represent the levels of infrastructure sufficiency for a H2 port, with 1=Non-existent, 3=Inadequate, 5=Acceptable, 7=Adequate, and 9=Satisfactory. Additionally, the readiness levels of critical factors for an efficient and effective H2 port were measured on a nine-point Likert scale, with 1=Idea, 3=Actionable plan, 5=Development, 7=Validation/Demonstration, and 9=Ready for implementation.
The decision to use a nine-point Likert scale was based on two primary reasons. Firstly, Miller concluded that humans' unidimensional judgment span is usually seven plus-minus two, which means the suitable number of comparisons for a human to judge at a time is between five and nine [230], with nine being the upper limit. Secondly, the use of a nine-point Likert scale is prevalent in evaluating readiness levels across various industries [231-233].

5.2.5 Risk Assessment

To evaluate the operational risks associated with H2 in ports, the risk matrix method was utilised. Given the limited academic literature on risk matrices for H2-related projects, this study created a 5x5 risk matrix based on an industrial HAZID report of a H2-related project in Ireland [234], as shown in Fig. 14. Tab. 14 and Tab. 15 present the scales for the likelihood of hazardous event occurrence and the severity of consequences, respectively. The risk matrix employs five different risk ratings, which are described in Tab. 16.

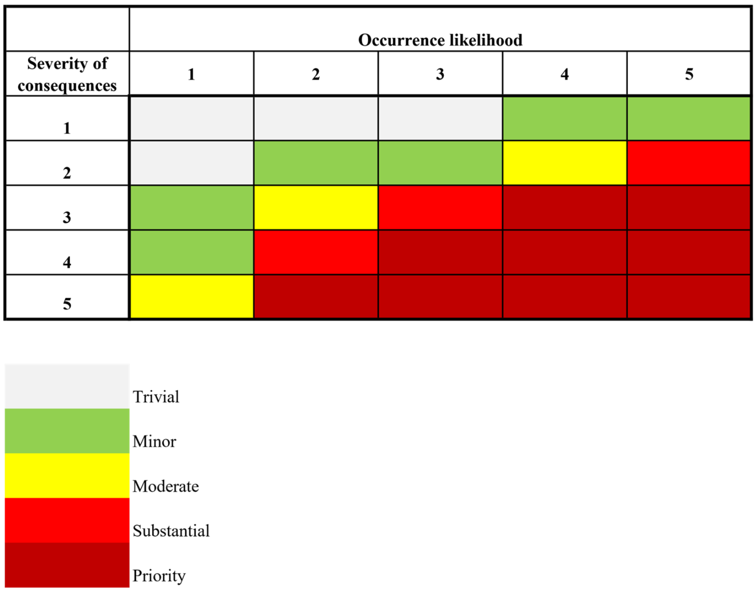


Fig. 14 Risk matrix

Tab. 14 Scale descriptions for occurrence likelihood

Scale	Expression	Description
1	Very low	Once in the life cycle of the whole sector/industry
2	Low	Once in the life cycle of the system in a port
3	Medium	Once in ten years in the system in a port
4	High	Once in a year in the system in a port
5	Very high	Once in a month in the system in a port

Tab. 15 Scale descriptions for severity of consequences

Scale	Expression	Description	
1	Minor	People	Slight injury or heath effect (first aid or medical treatment)
		Assets	Slight damage
		Environment	Slight effect (local scale, short term damage - weeks)
		Reputation	Slight impact (short term local concern; no suspension of port operations)
2	Moderate	People	Minor injury or heath effect (restricted work case or lost time injury)
		Assets	Minor damage
		Environment	Minor effect (local scale, short term damage - months)
		Reputation	Minor impact (short term national concern; short term suspension of port operations)
3	Major	People	Major injury or heath effect (partial disability)
		Assets	Moderate damage
		Environment	Moderate effect (local scale, short term damage - years)
		Reputation	Moderate impact (medium term national concern; medium term suspension of port operations)
4	Critical	People	≤3 fatalities, or permanent total disabilities
		Assets	Major damage
		Environment	Major effect (local scale, long term damage - decades)
		Reputation	Major impact (regional or persistent national concern; long term suspension of port operations)
5	Catastrophic	People	>3 fatalities
		Assets	Massive damage/ total loss
		Environment	Massive effect (regional scale, permanent damage)
		Reputation	Massive impact (global concern and media coverage; permanent closure of the port)

Tab. 16 Risk ratings

Risk level	Action
Trivial	No action is required for scenarios with such low risk levels.
Minor	No additional controls are required in most cases. Consideration may be given to a more cost-effective solution or improvement that imposes no additional cost burden. Monitoring is required to ensure that controls are maintained.
Moderate	Efforts should be made to reduce the risk, but the cost of prevention should be carefully measured and limited. Risk reduction measures should be implemented within a defined period. Where a moderate risk is associated with a scenario whose consequences are in the category of Critical or Catastrophic (Severity Rating 4 or 5) further assessments may be necessary to establish more precisely the likelihood of harm as a basis for determining the need for improved control measures.
Substantial	The activity should not be started until the risk has been reduced. Considerable resources may have to be allocated to reduce the risk. Where the risk involves a current activity, urgent action should be taken.
Priority	The activity should not be started or continued until the risk has been reduced. If it is not possible to reduce risk, even with unlimited resources, this activity must be prohibited.

5.2.6 Ethics Approval and Administration of Survey

Prior to the survey distribution, an amendment with survey questionnaire in support of the initial ethics approval for interview was submitted to the University of Tasmania Human Research Ethics Committee and approved. The online survey was conducted from 28 March to 22 May 2023.

5.3 Results

The results are discussed in categories according to questionnaire sections in the following.

5.3.1 Demographics

A total of 22 responses were received, representing a response rate of 34%. As shown in Fig.15 and Fig.16 where there is a reasonable distribution of experts from different countries (13 Australia, 7 Japan and 2 the UK) and different sectors (9 Port company/authority, 5 port/terminal operator, 3 exporter, 9 producer, 2 importer).

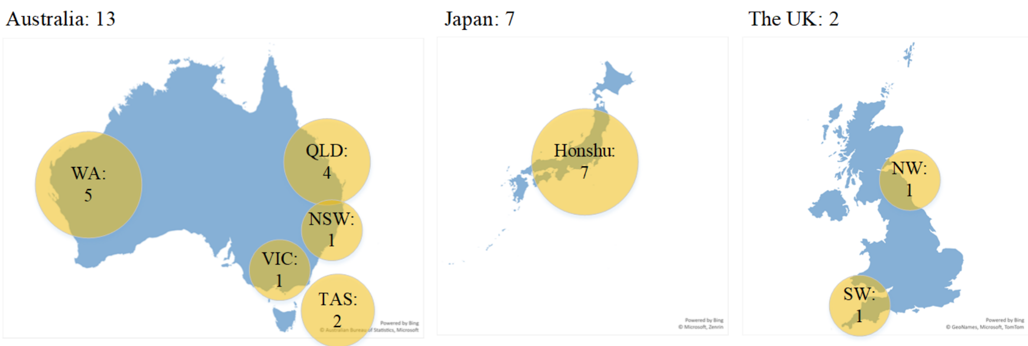
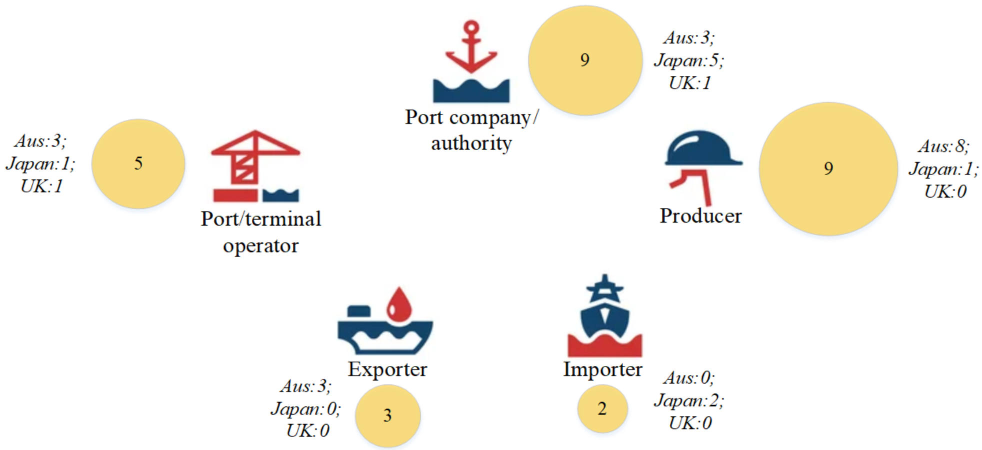


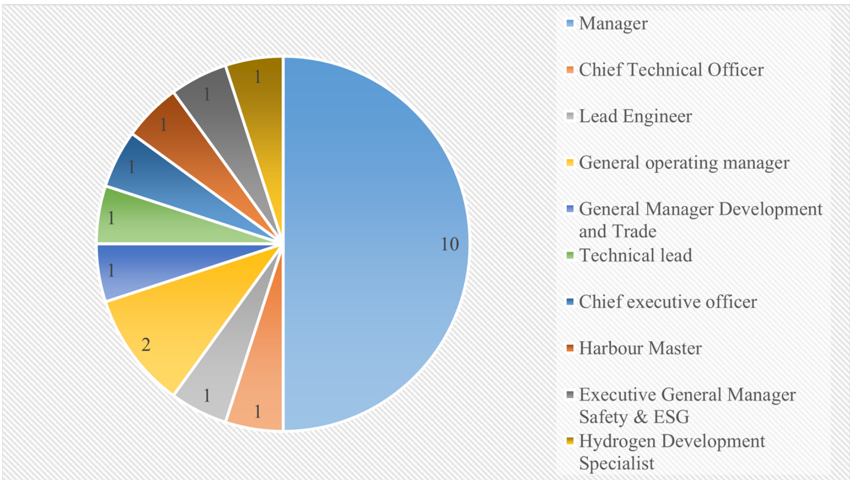
Fig. 15 Country distribution of the participants



Note ∶ Some participants indicated multiple fields.

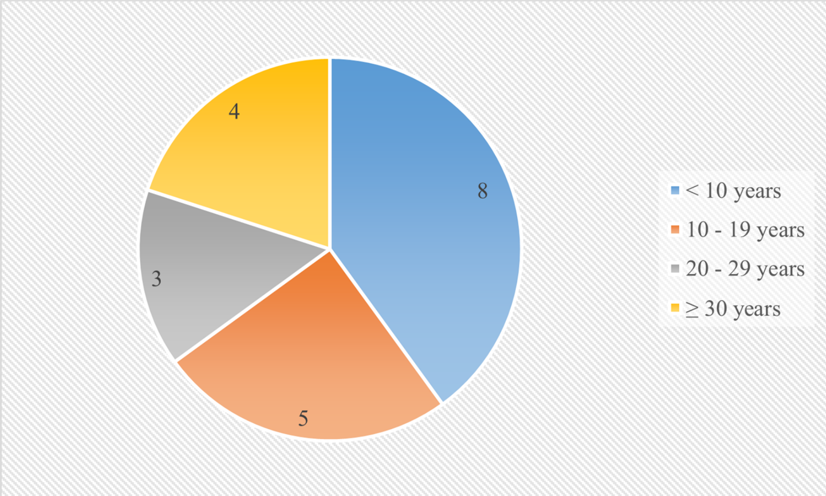
Fig. 16 Sector distribution of the participants

Fig. 17 and Fig.18 present the professional role and service time distribution of the participants respectively, showing the representativeness of participants' expertise and knowledge in the research area. As shown in Fig. 17, most of the participants were of manager position or above, for example CEO, General Manager, Harbour Master, Executive General Manager. Of notice is that four participants were engineering specialists in the research area i.e., Lead Engineer, Chief Technical Officer, Technical Lead and Hydrogen Development Specialist. Regarding the working experience, 60% of the participants were of working experience in this field more than 10 years, with 4 more than 30 years, 3 between 20-29 years, and 4 between 10-19 years.



Note: Few participants did not indicate their roles. ESG represents Environment, Social, and Governance

Fig. 17 Professional role distribution of the participants



Note: Few participants did not indicate their service years.

Fig. 18 Professional service time distribution of the participants

5.3.2 Hydrogen Forms for Trade and Utilisation

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

(1) Type of Trade for H2

Fig. 19 illustrates the distribution of the types of trade that participants intended to conduct through ports. Two responses of "Import" were from Japan, while all the "Export" responses were from Australia. The responses categorised as "Both" were from both Australia and Japan. The participants from the UK did not respond this question.

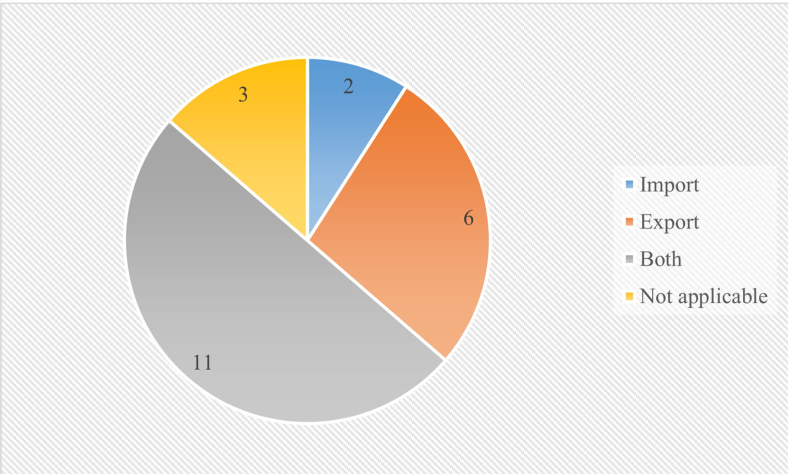


Fig. 19 Distribution of the types of trade

(2) Hydrogen Forms for International Trade

Fig. 20 depicts the distribution of forms of H2 that participants planned to produce, export, or import. Ammonia exhibits the highest counts, followed by LH2, LOHCs, CH2 and methanol in decreasing order. Fig. 21 displays the ranking of H2 forms based on their suitability for international trade over a 10-year timeframe, arranged from the most to the least likely possibility. Ammonia is expected to be a prominent H2 medium in terms of international trade, followed by LH2, methanol, LOHCs, and CH2.

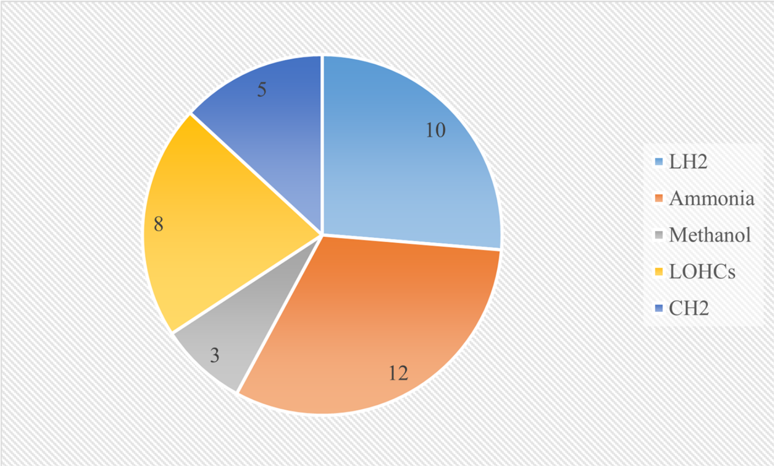


Fig. 20 Distribution of hydrogen forms for production, exporting, or importing

Fig. 21 Rank of hydrogen forms in terms of their suitability for international trade in a 10-year time frame

(3) Hydrogen Utilisation in Ports

Fig. 22 illustrates the participants' intention to utilise H2 or its derivatives for decarbonising ports' assets. No participants provided negative responses. Fig. 23 shows the distribution of ports' assets that have the potential to be decarbonised using H2 or its derivatives. Forklifts received the highest counts (11), followed by yard trucks (8), tugboats (6), and pilot boats, harbour crafts, bunker barges, and container movers/reach stackers with 5 counts respectively.

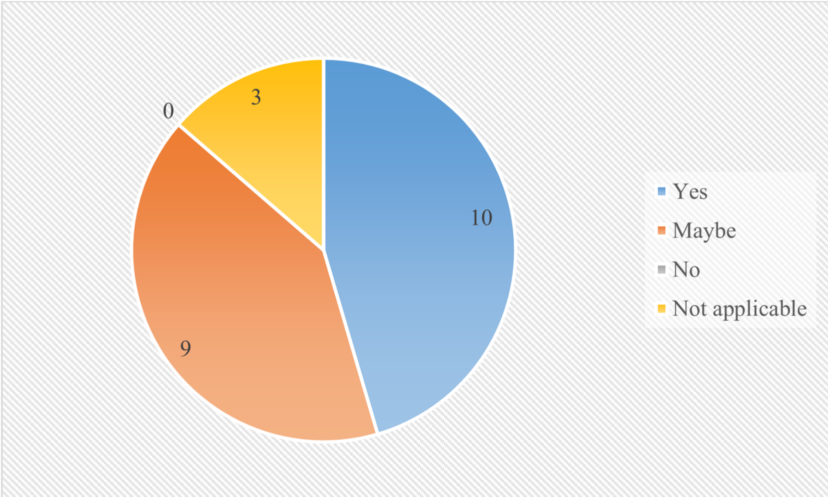


Fig. 22 Participants' intention to utilise hydrogen in ports

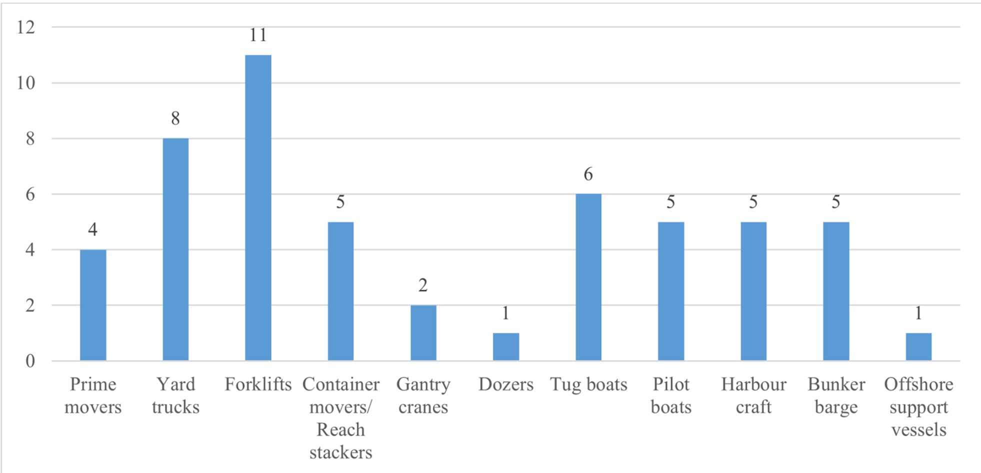


Fig. 23 Distribution of ports' assets that will be decarbonised using hydrogen or its derivatives

H2 or H2-based fuel refuelling or bunkering service has the potential to become an important business for ports, as it can aid in decarbonising both land transport and maritime shipping sectors. Fig. 24 displays the participants' intention to provide such services. Thirteen participants responded 'yes' and six answered 'maybe', while only one participant provided a 'no' response. Fig. 25 presents the distribution of fuel types that participants plan to provide for refuelling or bunkering. Twelve participants expressed a preference for providing ammonia as the primary fuel, followed by methanol (9), and LH2 and CH2 (gained an equal attention of 8).

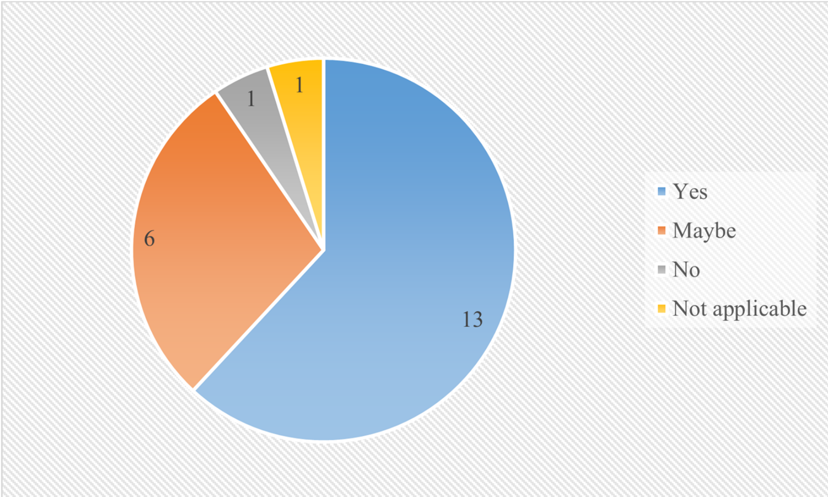


Fig. 24 Participants' intention to provide refuelling or bunkering services

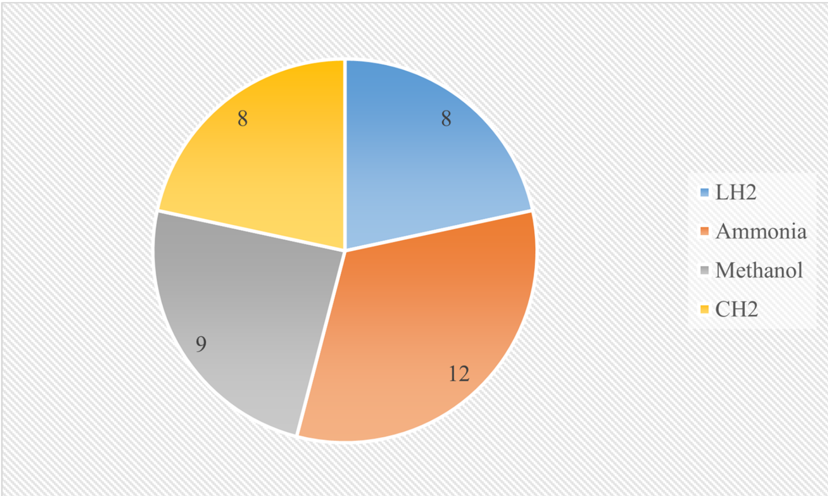


Fig. 25 Distribution of fuel types that participants plan to provide for refuelling or bunkering

5.3.3 Infrastructure Requirement and Sufficiency for Hydrogen Ports

Survey participants were asked to indicate the requirement and sufficiency levels of port infrastructure and facilities for managing the different forms of H2 they plan to export or import. Fig. 26 shows that participants considered safety equipment, and monitoring and control systems (21 counts for both) being the most required infrastructure and facilities, followed by storage tanks (20), loading/unloading facilities (19), berths (15), liquification facilities (15), pipelines (normal temperature) (14) and pipeline (cryogenic temperature) (14). The least required port infrastructure and facilities were refuelling stations. Additionally, two Australian participants provided comments in their responses suggesting that bunkering barges were required infrastructure for Australian H2 ports.

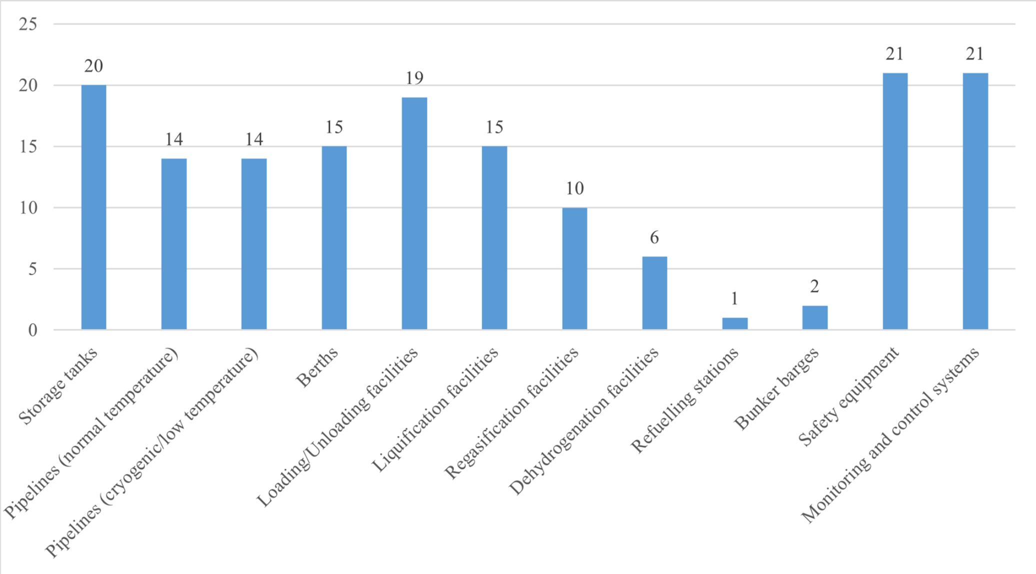


Fig. 26 Response count for each infrastructure or facility

Fig. 27 further presents their corresponding sufficiency levels in Australia, Japan, and the UK. It shows that the sufficiency levels for all port infrastructure and facilities are below 5 across the three countries except berths about 5 in Japan and the UK. The results indicate that overall port infrastructure and facility sufficiency fall below the acceptable range. In Australia, the twelve participants responded the sufficiency level of infrastructure and facilities being inadequate or non-existent. The highest one was safety equipment (4.31), followed by berths (4) and monitoring and control systems (3.58). The rest were below 3, with storage tanks, pipelines, loading and unloading facilities between 2 and 3, liquification and regasification facilities between 1and 2, and dehydrogenation facilities non-existent. Although two respondents suggested bunkering barges are required for Australian H2 ports, they are non-existent. In Japan, the sufficiency level of berths was just acceptable (5). The rest were inadequate mainly between 2 and 3 except safety equipment of 4.66 and monitoring and control systems of 4. In the UK, only berth had the acceptable sufficient level (5), the rest were inadequate between 3.5 and 4.5.

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					4				
5	Loading/Unloading facilities	12			2.77						
6	Liquification facilities	8		1.89							
7	Regasification facilities	4		1.33							
8	Dehydrogenation facilities	1		1							
9	Safety equipment	12					4.31				
10	Monitoring and control systems	12				3.58					
11	Truck refuelling stations	0									
12	Bunkering barges	2		1							

(a) Australia

No.	Infrastructure or facility	Response count	Sufficiency Level (1 Non-existent, 2, 3 Inadequate, 4, 5 Acceptable, 6, 7 Adequate, 8, 9 Satisfactory)
1	Storage tanks	6	2.83 ▽
2	Pipelines (normal temperature)	4	▽ 3
3	Pipelines (cryogenic/low temperature)	5	▽ 2.4
4	Berths	4	▽ 5
5	Loading/Unloading facilities	7	▽ 2.14
6	Liquification facilities	6	▽
7	Regasification facilities	5	▽ 2
8	Dehydrogenation facilities	3	▽ 3
9	Safety equipment	6	4.66 ▽
10	Monitoring and control systems	6	▽ 4
11	Truck refuelling stations	1	▽ 2
12	Bunkering barges	0	

(b) Japan

No.	Infrastructure or facility	Response count	Sufficiency Level (1 Non-existent, 2, 3 Inadequate, 4, 5 Acceptable, 6, 7 Adequate, 8, 9 Satisfactory)
1	Storage tanks	2	▽ 3.5
2	Pipelines (normal temperature)	2	▽ 4.5
3	Pipelines (cryogenic/low temperature)	1	▽ 3.5
4	Berths	1	▽ 5
5	Loading/Unloading facilities	2	▽ 3.5
6	Liquification facilities	1	▽ 4
7	Regasification facilities	1	▽ 3.5
8	Dehydrogenation facilities	0	
9	Safety equipment	2	▽ 4
10	Monitoring and control systems	2	▽ 4
11	Truck refuelling stations	0	
12	Bunkering barges	0	

(c) The UK

Fig. 27 Sufficiency levels for infrastructure and facilities

5.3.4 Berth Utilisation

From port operation and management perspective, common-use berths offer flexibility and cost efficiency. However, they may lack control and customisation so that pose security and safety concerns. Dedicated berths provide enhanced control and tailored infrastructure but may have capacity constraints, higher costs, and potential underutilisation. The choice depends on factors like port requirements, operational needs, and management strategies. As H2 supply chains are still in their early stages of development, the way of berth utilisation is under consideration. Fig. 28 presents the participants' preferences regarding the utilisation of common-use berths or dedicated berths. Most participants expressed a preference for using dedicated berths. Some comments were made by participants that explain why they supported dedicated berths:

- A dedicated berth has existed.
- Multi-user port facilities need to support energy trade flows which are regular and must be safe and reliable and cost competitive. This can conflict with seasonal trades with other jetty products.
- Depending upon the project schedule and throughput, the use of common-use berth (multiple product berth) will be challenging due to the hazardous nature of H2 and its derivatives.
- A dedicated berth is much easier to use and therefore preferred for exporting H2 and its derivatives.

On the other hand, some participants expressed their preference for common-use berth as a bulk liquid berth with multiple loading arms can cater for a range of H2 derivatives.

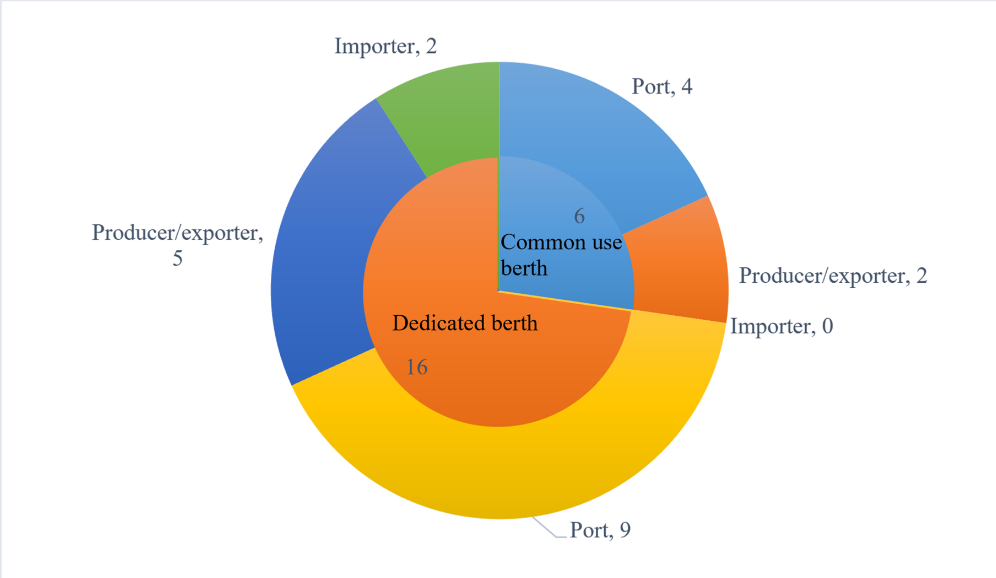


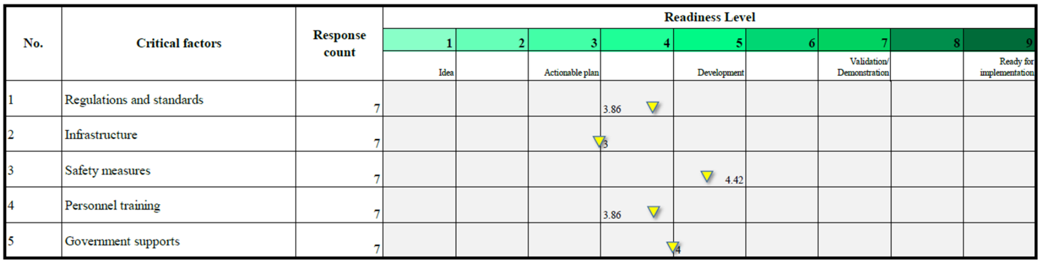
Fig. 28 Participants' intention to use common-use or dedicated berth

5.3.5 Readiness Levels of Critical Factors for Efficient and Effective Hydrogen Ports

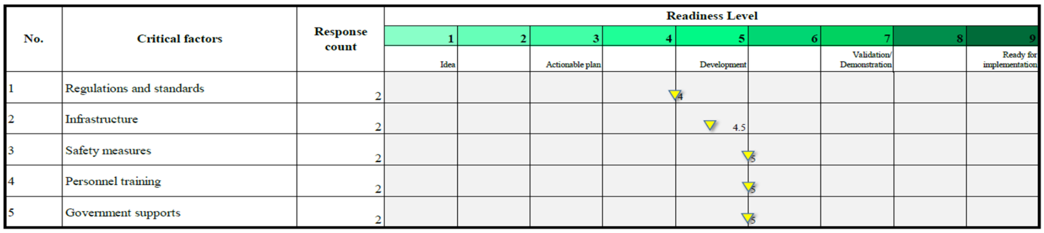
Based on the interview results, five critical factors for efficient and effective H2 ports were identified namely, regulations and standards, infrastructure, safety measures, personnel training, and government support. Participants were asked to assess the readiness levels of these factors. As shown in Fig. 29, the readiness levels of all factors are above 3 but below 5 across Australia, Japan and the UK except safety measures (5.15) in Australia, indicating that the critical factors were in development stage or below. In Australia, personnel training and government supports are of the lowest readiness level, while in Japan and the UK infrastructure and regulations and standards are the lowest, respectively. Safety measures across the three countries is of the highest readiness level.

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			
2	Infrastructure	13					4				
3	Safety measures	13						5.15			
4	Personnel training	13				3.07					
5	Government supports	13				3.07					

(a) Australia



(b)Japan



(c)The UK

Fig. 29 Readiness levels of critical factors for efficient and effective hydrogen ports

Three participants suggested additional critical factors below for efficient and effective H2 ports.

- Need to have clear mechanisms to manage carbon intensity across the value chain as well as covering the cost gap.
- Environmental permitting and commercial structures to enable the trade flows.
- Common regulations, safety measures and training across all jurisdictions.

5.3.6 Operational Risks Associated with Hydrogen in Ports

The survey specifically addresses the operational risks associated with gaseous H2 (GH2) and LH2. GH2 was not considered as a commodity due to its limitations in cost-effectiveness. Instead, it was considered as process gas and fuel gas for ports' energy users. The focus is placed on these forms of H2 as other H2 derivatives such as ammonia, methanol, and LOHCs have been extensively operated in ports for many years, leading to the establishment of robust risk management systems.

The risk assessments conducted in this research were not project-specific; instead, they were general assessments aimed at obtaining participants' overall risk perceptions regarding H2 ports. The mitigations in these assessments were not explicitly specified, but rather based on current standards, industry practices, and participants' experiences. Since these assessments are broad in nature, individual participant weights were not taken into consideration. Consequently, the results were derived from average values representing the likelihood of hazardous event (HE) occurrences and the severity of their consequences. Tab. 17 presents the identified hazardous events (HEs) for GH2 and LH2. Figs. 30 and 31 present the risk ratings of GH2 and LH2 respectively.

Tab. 17 Hazardous events for gaseous hydrogen and cryogenic liquid hydrogen

HE NO.	GH2	HE NO.	LH2
G1	Leaks in equipment	L1	Storage tank spills
G2	Leaks in pipelines	L2	Leaks in pipelines
G3	Unintended venting	L3	Leaks in transfer hoses or loading/unloading arms
G4	Leaks due to sabotage	L4	Unintended venting
G5	Fire	L5	Spills due to ship crashes (loaded ships)
G6	Explosion	L6	Spills caused by mechanical damage due to performing multiple activities at the same time
		L7	Spills due to sabotage
		L8	Fire
		L9	Explosion

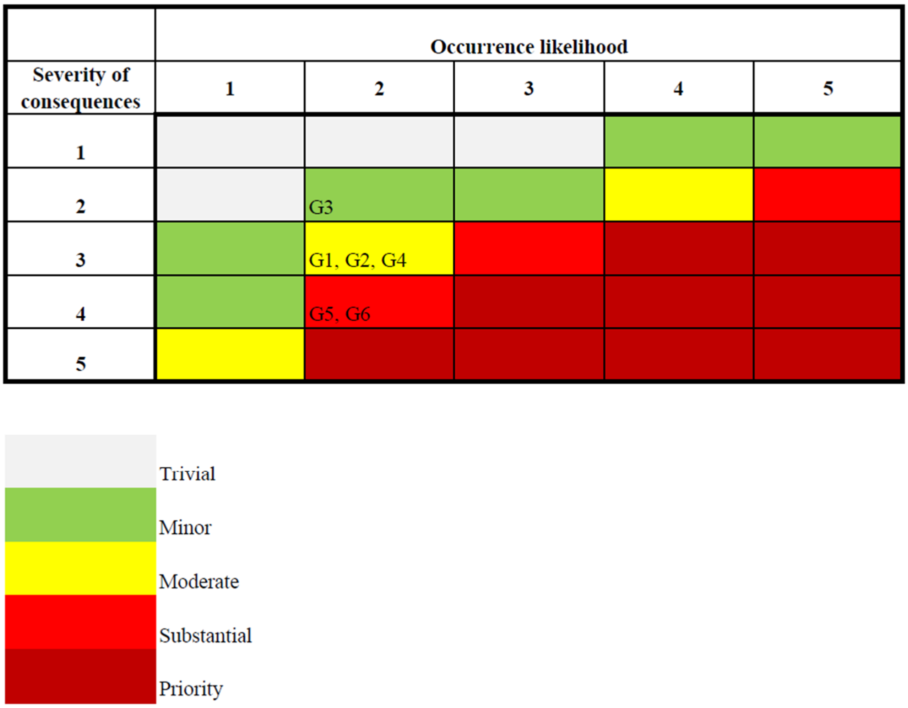


Fig. 30 Risk ratings of gaseous hydrogen

	Occurrence likelihood				
Severity of consequences	1	2	3	4	5
1					
2		L4			
3		L1, L2, L6, L7,	L3		
4	L9	L5, L8			
5					

Trivial

Minor

Moderate

Substantial

Priority

Fig. 31 Risk ratings of cryogenic liquid hydrogen

Regarding GH2-associated operational risks, Fig. 30 indicates that hazardous events G1, G2 and G4 are classified as having a "Moderate" risk rating, while G5 and G6 are categorised as "Substantial." In the case of LH2, hazardous events L4 and L9 are considered to have a "Minor" risk rating, while L1, L2, L6 and L7 fall into the "Moderate" risk rating. Hazardous events L3, L5 and L8 are classified as "Substantial." It is worth noting that no non-hazardous events, whether for GH2 or LH2, are categorised as "Priority".

5.4 Discussion

The online survey results provided useful insights from the perspectives of port companies/authorities/operators, H2 producers, exporters, and importers on the H2 forms for trade and utilisation, requirement for and sufficiency of port infrastructure and facilities, berth utilisation, readiness of critical factors, and operational risks. This section discusses the findings.

5.4.1 Hydrogen Forms

For production and trade, in line with the findings of the interview study, ammonia is the primary H2 carrier as per current industry's perspective in the short term. Whether being a medium for H2 transportation or an alternative fuel, ammonia attracted the most attention, while LH2, CH2, LOHCs, and methanol also received considerable focus. Some ports considered methanol as an option for H2 transportation. However, the availability of feedstock, such as CO2, to produce methanol in large quantities poses a challenge in certain locations. Only a few participants expressed interest in LOHCs and CH2 as their preferred choices.

In terms of suitability for international trade of H2 forms, ammonia was ranked first, followed by LH2, methanol, LOHCs, and CH2. There are four key reasons for ammonia's top ranking: Firstly, in relation to GHG emissions, ammonia demonstrates relatively favourable performance from both the "well-to-wake" and "tank-to-wake" perspectives. Secondly, ammonia can be directly utilised as a fuel and boasts a relatively high energy density. Thirdly, the storage and transportation conditions for ammonia, such as temperature and pressure, are comparatively manageable [106], compared to LH2. Fourthly, existing infrastructure is readily available for ammonia utilisation. Interestingly, liquid H2 was ranked the second for trade although there are various challenges associated with cryogenic storage and transportation conditions. The experimental shipment of LH2 between Australia and Japan may have created confidence among the participants. Methanol, as the third-ranked carrier for international H2 trade, possesses advantages such as the capability for storage and transport under ambient conditions, direct use as a fuel, and a mature infrastructure. Additionally, the limited technological maturity of LOHCs and the low efficiency of long-distance transportation for CH2 place these two options at the bottom of the ranking. Of noticed is that Japanese proponents are actively exploring using LOHCs as H2 carriers, benefitting from their ease of handling and the ability to utilise existing infrastructure. In comparison, CH2 is primarily suitable for short-distance shipping through ports due to its relatively lower transportation efficiency.

Regarding the use of H2 within the port, many participants expressed its potential, but those who gave a definite positive answer did not constitute the majority. This may be due to the uncertainty about the demand for H2 and its derivatives in decarbonising port assets and ships. For instance, vehicles and machinery within the port can be electrified to achieve zero emissions. Further research is needed to determine the advantages and disadvantages between electrification and the adoption of H2 as two potential solutions. As for providing fuel bunkering for ships, respondents from ports faced difficulty in deciding regarding which fuel to prioritise, as the shipping industry is still exploring the feasibility of various fuels.

5.4.2 Infrastructure

In terms of infrastructure sufficiency, overall, the three countries were at a relatively early stage. Comparatively, Australian respondents appeared to be more optimistic. The reasons behind this are, on one hand, the Australian government intends to transform Australia into a global leading H2 exporting country, and therefore provides relatively greater support in terms of policies and funding for H2-related projects. On the other hand, many Australian ports have accumulated substantial infrastructure for exporting LNG and other chemicals, some of which can be modified to accommodate the export of H2 and its derivatives. Even in the case of constructing new technological facilities, the knowledge and experience gained previously will accelerate the progress.

5.4.3 Berth Utilisation

When it comes to berth usage, most respondents preferred dedicated berths. This choice is likely driven by safety considerations, as hazardous liquid cargoes like LNG typically require dedicated berths to maintain a safe distance. However, as revealed from interviews, during the initial stages of H2 energy trading, individual traders may have relatively low trade volumes, and employing dedicated berths could lead to wastage of resources. Consequently, the concept of shared berths may be viable in the early phases of H2 trading. Naturally, it is crucial to prioritise risk control when utilising shared berths. As the supply chain expands, significant proponents with higher trade volumes could potentially utilise dedicated berths, similar to the current practice for LNG. Consequently, it would be advisable to develop berth management protocols that address both short-term common-use berths and long-term dedicated berths.

5.4.4 Readiness of Critical Factors

Regarding the readiness factors, including regulations and standards, infrastructure, safety measures, personnel training, and government supports, to enhance the safe and efficient operation of H2 ports, the three countries were relatively similar and currently at a moderately lower stage. To overcome these challenges, this study has discussed the solutions in section 4.4 based on the interview findings.

5.4.5 Risk Perceptions

According to the risk matrix, both GH2 and LH2 operations within the port area do not have any hazardous events reaching the highest risk level. However, there are some events that reach "Substantial" and "Moderate" risk levels. It is crucial to implement additional risk mitigation measures to address these concerns. In developing relevant standards and risk management protocols, it is essential to prioritise mitigating these unacceptable hazardous events.

It is important to highlight that the risk assessment in this research is based on macro-level evaluation using existing H2-related technical standards and operational experience, and conventional risk reduction measures have already been considered. This means that a certain cost needs to be invested to reduce these risks above the "Minor" level when implementing H2 projects at the port. However, it should be noted that the risk assessment conclusions drawn from this research are not specific to any port and cannot be used as a basis for determining the risk level of H2 projects at ports.

6. Operational Framework for a Hydrogen Port

This section suggests a framework for operating H2 logistics and application of H2 technology in ports (H2 Port).

6.1 Overview of Operational Framework

Based on the interview and survey results, this project identified the fundamental characteristics required for an H2 port. Several essential factors need to be considered by a port to undergo the necessary transformation into an H2 port. To establish a clear operational process for an H2 port, this project devises an operational framework, as shown in Fig. 32, based on technological advancement and the findings from the interviews and surveys. The proposed framework provides a comprehensive overview of the entire process involved in the port's H2 transformation, by encompassing the following key components:

- Provision of essential elements: The framework outlines the crucial elements necessary for the successful conversion of a port into an H2 port.
- User-oriented working process: The framework presents a detailed working process that takes into consideration the needs and requirements of the port. It provides guidance on how to effectively incorporate H2 technology into the port's operations.
- Consideration of government support: The framework incorporates aspects related to government support, emphasising the significance of policies, incentives, and regulations to foster the transformation of a port into an H2 port.

6.2 Essential Elements for H2 Ports

As depicted in the upper section of Fig. 32, this research focuses on the 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. These include materials and components for constructing wind or solar farms, water electrolysers, and port infrastructure. The shift in functions and roles may differ from the traditional role of many Australian ports that primarily export chemicals or gas. Consequently, new general cargo berths and additional facilities such as roads and cranes are required to accommodate the importing task.

The sites for H2 production and conversion can be situated near or within the ports. Pressurised or low-temperature pipelines are essential for H2 and/or its derivatives transportation. Storage tanks for H2 and/or its derivatives 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 to transport H2 and its derivatives, tank-container berths and stock yards become necessary. Subsequently, H2 or its derivatives can be shipped to the importing ports.

On the right side of Fig.32, an H2 importing port is equipped with liquid bulk berths and/or container berths and yards. The liquid bulk commodity can be stored in tanks and, if needed, reconverted into pure H2 form. The H2 is then transported to the H2 demand market through pipelines or road tankers. ISO tanks can also be transported to the market using road trailers.

To facilitate the use of H2 within ports, various vehicles, and equipment such as trucks, forklifts, and service boats can potentially utilise H2 as fuel. Consequently, the establishment of refuelling stations becomes necessary to cater to these H2-dependent users. Moreover, to supply H2-based fuel to large vessels, the presence of bunkering barges is essential. These barges serve as key infrastructure for delivering H2 to maritime vessels in need.

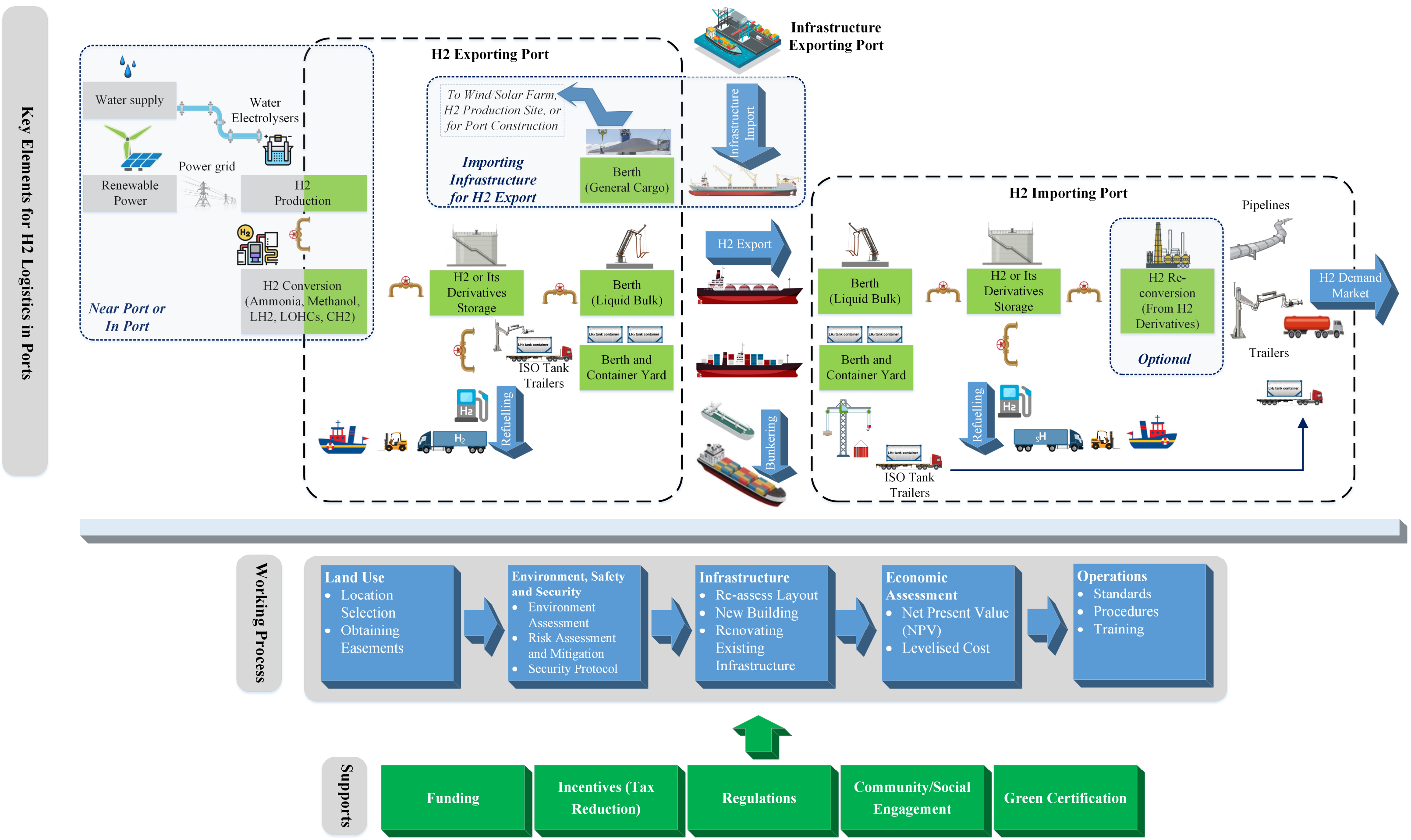


Fig. 32 Framework for operating H2 logistics and application of H2 technology in ports

6.3 Working Process

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

6.3.1 Land use

Step 1 is to acquire sufficient land for renewable power generation, power grid access, water supplies, H2 production, and H2 conversions. This step is integral to the transformation of H2 ports and is thus considered in the working process.

One of the primary challenges in implementing renewable power generation, establishing power grid access, ensuring water supplies, and facilitating H2 production and conversions is acquiring a large enough land area. Obtaining such land requires careful consideration and planning. Below is an overview of the process:

- Land location selection:
  The first step is to identify suitable locations for the project. Various established tools and methodologies can aid in this process [235]. These tools can help evaluate factors such as solar or wind potential, proximity to existing power infrastructure, accessibility to water sources, and other relevant considerations. Thorough analysis and assessment are essential to ensure optimal site selection.
- Assessing optional locations:
  Once potential locations are identified, a thorough evaluation of each site's feasibility should be conducted. This assessment involves considering factors like land availability, environmental impacts, local regulations, community support, and other relevant criteria. Careful evaluation will help determine the most viable options for further consideration.
- Obtaining easements:
  Once suitable locations are identified, the next step is to secure the necessary easements or rights to access and use the land. This process involves negotiating with landowners, obtaining legal agreements, and addressing any potential concerns or conflicts. Adequate attention should be given to securing long-term access to the land, allowing for sustainable and uninterrupted operation of renewable power generation systems, power grid infrastructure, water supply facilities, and H2 production and conversion facilities.

By following these steps, the challenging task of acquiring the necessary land for renewable power generation, power grid access, water supplies, H2 production, and H2 conversions can be addressed.

6.3.2 Environment, Safety, and Security Assessment

Step 2 involves evaluating the environmental, safety, and security considerations, critical to ensure responsible and sustainable implementation of H2 technologies.

H2 derivatives such as ammonia, methanol, and LOHCs are known to be toxic, and they can have significant environmental impacts. 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 quantitative safety risk assessments. These assessments will help identify and mitigate any potential hazards associated with the use of H2. Both the environmental and safety assessments mentioned above are essential for obtaining the necessary social license to operate. By conducting these evaluations, companies can demonstrate their commitment to addressing potential risks and minimising the impact on the environment and public safety. In addition, existing security protocols at ports should be reviewed and potentially revised to account for the risks associated with handling these new commodities. Measures should be taken to prevent sabotage and restrict unauthorised access to hazardous areas, ensuring the safety and security of operations involving H2 derivatives.

6.3.3 Infrastructure

Step 3 focuses on the construction or renovation of port infrastructure to facilitate H2 trade and application.

To begin, the port layout should be thoroughly reassessed from a safety perspective. This assessment will help identify any necessary safety measures. For example, blast prevention walls and additional firefighting equipment may be required to enhance safety measures. The construction of new tanks, pipelines, berths, and refuelling stations may be necessary to accommodate the storage, transportation, and handling or using the new commodities. The infrastructure should be designed and built in accordance with established safety standards and protocols to ensure a secure and efficient movement of H2-related operations. In addition to new infrastructure, existing port facilities may need to be renovated or upgraded to meet the specific requirements for handling H2 and its derivatives.

6.3.4 Economic Assessment

Step 4 involves conducting an economic assessment, which plays a pivotal role in determining the pricing of H2 commodities.

It is crucial to consider the costs associated with port facilities, including both capital expenditure (CAPEX) and operational expenditure (OPEX), when calculating the final delivered H2 price. Moreover, obtaining the levelised port cost of H2 provides valuable insights into the overall cost dynamics. This step is also significant for the entire supply chain as it enables a thorough understanding of the port link in terms of investment and potential profit returns.

6.3.5 Operations

Step 5 focuses on the safe and efficient operation of an H2 port. To achieve this, it is imperative to adhere to international or local standards and guidelines.

Developing well-defined port operation procedures is essential to ensure smooth operations. Additionally, providing comprehensive education and training to port staff and relevant personnel is crucial to minimise human errors and maintain a high level of safety throughout the operation. By prioritising safety measures and investing in training, the H2 port can function effectively and mitigate potential risks.

6.4 Required Support

To achieve the H2 transformation of ports, comprehensive support from governments is necessary, as discussed in sections 4 and 5 of this report. Recognising the significance of this transition, governments should actively contribute to the advancement of H2 technologies within port operations.

One essential aspect of government support is providing funding opportunities. Financial assistance can help cover the substantial costs associated with developing H2 infrastructure, such as production and storage facilities, refuelling stations, and port equipment upgrades.

In addition to funding, governments can play a vital role by implementing favourable policies. These can include tax deductions or incentives that encourage investments in H2 ports. By offering tax breaks or financial incentives, governments can incentivise companies to adopt H2-powered solutions and promote the growth of the H2 industry within ports.

Furthermore, establishing specific regulations and standards for H2 port operations ensures safety, reliability, and interoperability. Governments can collaborate with industry experts to develop comprehensive guidelines and best practices that address technical aspects, safety protocols, and environmental considerations. These regulations provide a clear framework for port operators, ensuring that H2 facilities and operations meet stringent standards, thus instilling confidence in the industry and facilitating widespread adoption.

To establish an H2 port, involving local community's participation is essential to pursue social acceptance. They can engage in public consultations and information sessions to learn about the advantages and drawbacks of the H2 port establishment, increase awareness, and build support. The community can also advocate for the project by communicating its potential benefits, such as job creation and economic development, and expressing their endorsement to local policymakers and government officials. Additionally, they can provide input on the port's location and design, ensure environmental sustainability, and identify potential concerns or challenges during the planning and implementation process.

Green certification programs can also play a significant role in government support. By introducing certification schemes that recognise and reward ports for their sustainable practices and reduced GHG emissions, governments can incentivise port operators to embrace H2 technologies. Green certifications not only showcase a port's commitment to environmental responsibility but also enhance its reputation and competitiveness in the global market.

Overall, governments hold the key to fostering the H2 transformation of ports through strategic support measures.

7. Recommendations and Conclusion

This section provides strategies to overcome the challenges and barriers encountered by H2 ports and concludes the research.

7.1 Recommendations

This empirical research identified opportunities for ports' involvement in the H2 economy. However, there are significant challenges and barriers to ports' readiness in integrating in the global H2 supply chain. These include constraints to the accessibility of resources, insufficient infrastructure, lack of regulations and standards, insufficient understanding of H2 safety, lack of practical personal training, and obtaining social licence (acceptance). The following are the recommendations for managing these challenges.

- **Increase accessibility of resources**
  Land, renewable electricity, and water are vital resources for H2 production in or near ports. However, currently a significant challenge in accessing sufficient resources exists at potential H2 exporting ports. The primary obstacles are the limited availability of vacant land, the need for upgraded power grids, and inadequate water supply (either fresh water or desalinated sea water). To increase accessibility of resources, this research suggests the below solutions.
  - ➢ To secure land use, all stakeholders should enhance communication and negotiation to achieve a mutually beneficial social and economic benefits.
  - ➢ Collaboration with renewable energy providers should be fostered to ensure a consistent and reliable supply of renewable electricity. Investments should be made in upgrading power grids to meet the growing demand for H2 production.
  - ➢ Exploration of alternative water sources should be actively pursued to guarantee sufficient water supply for H2 production. Technological advancements have made desalinated seawater a viable option [236].
- **Accelerate port infrastructure development**
  In Australia, Japan, and the UK, the infrastructure and facilities required for H2 ports are still in an early stage of development. Furthermore, there is a lack of refuelling infrastructure, bunkering stations, and barges for ports that plan to utilise H2 within their operations or provide H2-based fuel supply services. For improving the readiness of infrastructure and facilities for H2 ports, the following strategies are recommended.
  - ➢ Ports are situated in the middle of the international H2 supply chain, and uncertainties regarding the upstream supply capacity and downstream market demand may affect investors' willingness for infrastructure investments. All parties along the H2 supply chain 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.
  - ➢ It is crucial to prioritise and expedite efforts to accelerate the deployment of necessary infrastructure and facilities. In the case of ammonia, methanol, and LOHCs, certain existing infrastructure and facilities can be utilised, making it feasible to initiate demonstration projects in the near future.
  - ➢ It is feasible to utilise common-use berths for demonstration projects, considering the low trade volume in the short term. Significant proponents with higher trade volumes could potentially utilise dedicated berths as the supply chain expands. Developing berth management protocols that address both short-term common-use berths and long-term dedicated berths is advisable.
  - ➢ 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 cryogenic liquid H2 storage and handling in ports needs technological breakthroughs.

- To improve the readiness of infrastructure for H2 ports, investment required is significant. Although the governments in the three countries have provided some financial support to H2 projects. However, the current level of financial support for developing ports' infrastructure needs to be increased. Solutions could be:
  - Increase financial support and subsidies from governments for H2 ports to attract investment and alleviate the financial burden on port operators.
  - Public-private partnerships should be encouraged to leverage private sector investments and expertise.

- **Increase incentives for ports to support decarbonisation**
  This study discovered that ports understand the benefit of applying H2 in ports to support decarbonisation. However, there are barriers to the application, such as regulatory support, investment cost for replacement of H2 powered equipment, vessels, vehicles, and facilities. Also, most of the port companies/authorities operate as a landlord, it is the decision of their tenants or contractors whether H2 will be applied in their equipment and facilities. To enhance ports' role in supporting decarbonisation by utilising H2, governments could consider providing the following incentives for ports to support decarbonisation through H2 utilisation.
  - To provide direct financial incentives to ports for investing in H2 powering assets.
  - To implement tax reductions or other fiscal incentives for ports that contribute significantly to reducing GHG emissions. This will encourage ports to use H2 for powering their assets.
  - To establish an incentive mechanism to stimulate the creation of domestic H2 demand markets. This helps increase the certainty of demand for H2 production in or near ports and enhance ports' role in supporting decarbonisation for their regions. For example, if land transport i.e., truck and rail would adopt the H2 fuel cell technology, ports can offer refuelling stations for those trucks and rail travelling between ports and hinterland. Similarly, ports may provide H2 bunkering to aquaculture vessels if they are powered by H2.

- **Adopt stakeholder collaboration approach for establishing regulations and standards**
  Various forms and derivatives of H2 require specific regulations and standards. In the case of ammonia, methanol, and LOHCs, existing regulations and standards are already in place, although adjustments may be necessary to accommodate the scaled-up volumes at ports. While numerous regulations and standards exist for land based H2 supply chains, there is a significant gap in regulations and standards concerning H2 handling and utilisation within ports. Currently, there is a lack of port-specific regulations and standards pertaining to infrastructure, safety, and environmental aspects necessary for the scaling up of H2 and its derivatives. To address these challenges, collaboration between stakeholders is critical, and below strategies are suggested.
  - Governments and regulatory bodies (international or national) should collaborate to establish port-specific regulations and standards for H2 handling, infrastructure, safety, and environmental aspects. Both international and national standards can play crucial roles in shaping the regulatory framework within this emerging field. Internationally, the IMO, in addition to working on regulations on H2 shipping, can consider regulating ports handling and applying H2 to provide guidance for member states [237]. The IMO can play a role to internationally coordinate shipping and ports/terminals for H2 transport. Nationally, an H2 port regulation's structure should encompass several critical aspects to ensure safe operations. Firstly, it must prioritise work health and safety, safeguarding workers and the public from any risks associated with H2 operations. This involves implementing emergency plans, managing hazardous chemicals and atmospheres, and licensing major hazard facilities. Secondly, there should be provisions for environment protection and biodiversity conservation to address activities like waste disposal, pollution control, and handling environmental incidents. Additionally, the regulations must incorporate carbon credits, requiring project proponents to register under the carbon credit scheme and adhere to established carbon credit methodologies. Measurements are vital for trade purposes,

necessitating a mandatory framework for accurately measuring gases and liquids, including hydrogen and its derivatives. This entails pattern approval, verification, and in-service accuracy of measurement devices. Furthermore, the regulations should oversee the transport of dangerous goods by road and rail in ports, ensuring risk management during the transportation of hydrogen and its derivatives via trucks and trains. Protection of the sea is also crucial, regulating shipping pollution, incident reporting, and post-incident cleanup obligations, as well as controlling greenhouse gas and air pollutant emissions. Lastly, navigation regulations must be in place to govern international and domestic H2 shipping and seafaring. This encompasses various aspects like vessel certification, construction, crewing, qualifications and welfare, occupational health and safety, and the carriage and handling of cargoes.

  - 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.

- **Enhance understanding of H2 safety**

  Both underestimating and overestimating the safety risks of H2 are inappropriate. This research conducted a general risk assessment for gaseous and liquid H2, based on the survey participants' perceptions, and indicated that certain hazardous events were assigned unacceptable risk ratings and required the implementation of additional risk mitigation measures. Despite the research finding, there is no prior experience in handling H2 and its derivatives as commodities or using them as fuel in ports, from ports' perspective, there is still insufficient understanding of the safety risks associated with H2. Hence, it is important to:

  - Develop training programs and initiatives to enhance understanding of H2 safety risks among port personnel and relevant stakeholders.
  - Establish and disseminate the best practices and guidelines for H2 handling, storage, and transportation.
  - Share experience and collaborate with industries of expertise in handling hazardous materials that can help develop robust safety protocols for H2 in ports. Knowledge gained from the aerospace and LNG industries can be a valuable reference. In the aerospace industry, NASA's H2 safety standards system can serve as a significant reference for ensuring safety in H2 ports. In the LNG industry, the well-developed regulatory framework for LNG ships by the IMO and the comprehensive standard system established by the Society of International Gas Tanker and Terminal Operators (SIGTTO) over 60 years, covering port facilities, cargo operations, and ships [238], can provide guidance for the safe construction and operations of H2 ports and shipping.

- **Develop practical personnel training**

  Australia, Japan, and the UK have taken steps to design and offer H2 training programs for the emerging industry. There are currently some theoretical training programs available in the H2 industry. However, there is a noticeable lack of practical training, particularly when it comes to port operations. It is crucial to have well-trained and skilled professionals who can ensure safe and efficient functioning of an H2 port. To address the challenge of insufficient education and training, this research provides the following solutions.

  - Engaging professional experts from the aerospace industry who can provide practical knowledge and hands-on training exercises to enhance the skill set of port professionals in the H2 sector.
  - Developing practical training programs specific to H2 port operations, which cover handling procedures, emergency response protocols, and maintenance practices.
  - Forming partnerships between academic institutions, industry experts, and port authorities to provide comprehensive and hands-on training opportunities.

- Establishing continuous professional development programs to keep personnel updated with the latest technologies and safety practices in the H2 industry.

- **Promote public awareness to facilitate obtaining social license**

  At present, the public's comprehensive understanding of the social, economic, and environmental impacts of H2 ports is still limited. To facilitate obtaining social license, it is essential to:
  - 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 on H2 ports. Collaborative efforts can enhance credibility and provide unbiased information to the public.
  - Engage local community through dialogues, consultations, and regular updates to encourage participation and address concerns in project planning and decision-making.

7.2 Conclusion and further research

Ports play a crucial role in the global supply chain and transportation network, serving as hubs for trade and commerce. With the growing demand for H2 worldwide, ports have an opportunity to leverage their strategic location, infrastructure, and expertise to facilitate international H2 trade. Moreover, ports have the potential to become consumers of H2 as a source of energy for their operations, thereby reducing their carbon footprint. Currently, H2 ports are still in their early stages, and the academic and industrial communities still need to fully understand them, particularly in terms of their functions and the challenges faced. With this context, this research took the ports of Australia, Japan, and the UK as research subjects and explored how ports can be integrated into H2 supply chains, including their opportunities and challenges.

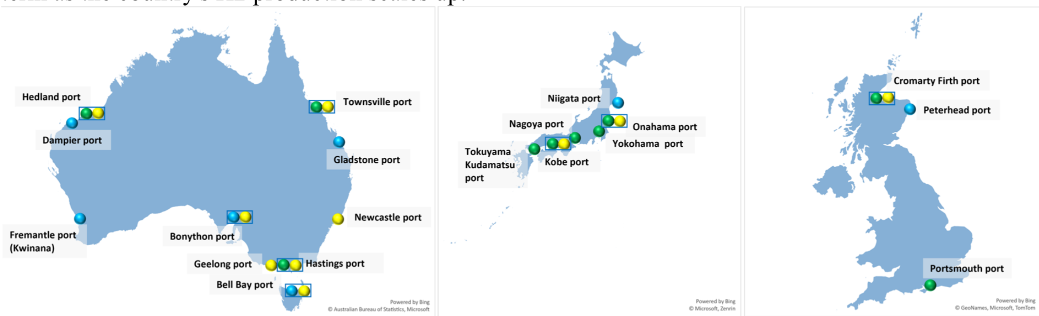
Following a thorough review of relevant H2 literature including academic articles, government reports and other industry reports, the research team interviewed and surveyed to key port focused H2 supply chain stakeholders in the three countries that critically examined the current state of the H2 industry. The empirical research identified potential early H2 ports and meticulously determined the requisite infrastructure and facilities necessary for the successful establishment of H2 ports. Subsequently, a quantitative evaluation of the operational risks associated with H2 in ports was conducted, alongside an extensive identification and analysis of the challenges and barriers hindering the H2 handling and application in ports. To streamline logistics operations and effectively integrate H2 applications in ports, an operational framework was developed. Finally, by synthesising the findings, this research provided informed recommendations to address the prevailing challenges and barriers concerning the logistics handling and utilisation of H2 in ports.

Interview outcomes revealed opportunities for ports in the H2 economy, including business transition (e.g., additional business or transitioning existing declining industry or activities); H2 production if close to renewable energy sources; increasing trade (export and import); improving utilisation of port infrastructure; supporting renewable energy's development (e.g., offshore wind); being resilient in terms of mixed energies for customers, and applying H2 in powering port assets.

With the opportunities, ports' major roles and functions within the emerging global H2 supply chains include ensuring sufficient infrastructure and facilities to facilitate different forms of H2 trade and other imported equipment for producing H2; decarbonisation of port assets by using H2; facilitation of domestic use of H2 to decarbonise their region; and coordination and collaboration with other stakeholders to ensure a safe H2 supply chain.

While there are numerous opportunities for H2 energy ports to promote the global energy transition and foster the growth of ports, there are challenges faced by ports in facilitating H2 logistics and application. From port development aspect, challenges include land use, uncertainty of H2 demand, lack of adequate infrastructure, insufficient education on H2 knowledge and technology, lack of safety standards and regulations, and obtaining social licence. For ports considering applying H2 for decarbonisation, they face challenges of regulatory support and costs associated with investment. From shipping perspective, scaling up H2 or ammonia transport using large carriers requires port infrastructure development such as depth or large storage tanks to accept them. The interview results also revealed that the governments of Australia, Japan, and the UK have offered financial support to H2 projects. Nevertheless, the current level of financial assistance for ports falls short of what is needed.

Survey outcomes further identified potential H2 ports in the three countries. Combining the findings from literature review and interviews, this research presents nineteen potential H2 ports in the three countries depicted in Fig.33. Out of these, ten ports are in Australia (Hedland, Dampier, Fremantle, Bonython, Geelong, Hastings, Bell Bay, Newcastle, Gladstone, and Townsville), six in Japan (Tokuyama Kudamatsu, Kobe, Nagoya, Yokohama, Onahama, and Niigata), and three in the UK (Portsmouth, Peterhead, Cromarty Firth). The Australian ports serve as exporting ports, whereas Japan's ports function as importing ports. As for the UK, it's ports currently have the potential to serve as importing ports in the short term, with the possibility of transitioning into exporting ports in the long term as the country's H2 production scales up.



Note: Yellow dots representing the ports identified by literature review; Blue dots representing the ports identified by Participant Group B in the interviews; Green dots representing the ports described by Participant Group A in the interviews

Fig. 33 Identified potential hydrogen ports

In terms of survey data, this research also quantitatively assessed the readiness of H2 ports to embrace the upcoming H2 economy. It collected quantitative data on the readiness of ports in various aspects including H2 forms, infrastructure, key factors facilitating efficient port operations, H2 utilisation within the port, and risks associated with H2 handling. In respect of H2 forms, survey participants considered that in a 10-year timeframe, ammonia was expected to be the primary carrier of H2 and traded through ports. The maturity of the technologies primarily drives this choice. Cryogenic LH2 was ranked second, although there are significant challenges to overcome in terms of large-scale storage technology, and methanol was ranked the third.

Survey participants considered safety equipment and monitoring and control systems being the most required infrastructure and facilities for H2 ports, followed by storage tanks, loading/unloading facilities, berths, liquification facilities, pipelines (normal temperature and cryogenic temperature). The least required port infrastructure and facilities were refuelling stations. The survey outcomes also revealed the sufficiency level of these port infrastructure and facilities, falling below the acceptable range (scale 5) across the three countries except berths about 5 in Japan and the UK. The results implies that overall port infrastructure and facility development for H2 ports is still in an early stage. Participants also indicated their preference of using berth when dealing trade of H2 and its derivatives. Many participants preferred dedicated berths to common use.

For the readiness level of critical factors for H2 ports i.e., regulations and standards, infrastructure, safety measures, personnel training, and government support, most of the survey participants in the three countries thought they were at a development stage or below.

Risk matrixes were generated based on the survey participants' perceptions on LH2 and GH2 operational risks in ports. The results show that both GH2 and LH2 operations within the port area do not have any hazardous events reaching the highest risk level. However, there are some events that reach "Substantial" and "Moderate" risk levels, which require risk mitigation measures.

Finally, this research developed a comprehensive operational framework to provide valuable guidance for ports seeking to embrace H2, based on the findings from interviews and surveys. The framework encompasses key components that are essential for the successful H2 ports' transformation process. It includes providing necessary elements to support the integration of H2 technology within the port's operations. The framework also emphasises a user-oriented working process that considers the specific needs and requirements of the port. Additionally, 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.

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 project analysed the opportunities and challenges faced by H2 ports and provided some approaches to overcome existing challenges. The issues on H2 ports and supply chains raised by this study are important for industry and academic research. Particularly, more regulations on reducing CO2 emission have been imposed by countries, for example, the EU has imposed the limitation of the use of internal combustion vehicles after 2030. Therefore, the alternative fuel such as hydrogen becomes critical. Global research institutions such as universities in the EU have been proactively involved in hydrogen projects to realise and manage the use of the new source of energy.

Due to the nascent stage of H2 ports, the limited number of interviewees and survey respondents in this study poses a limitation. 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, including emerging economies, to gain a deeper understanding of the global progress made in H2 ports and their challenges. Second, this research has provided general recommendations for planning and implementing H2 ports, further studies could be focused on developing detailed strategies concrete solutions to the challenges, from the aspects of regulatory, environmental, financial, and technical, and verifying them through a broader survey, which can be used for H2 port actors. 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. Furthermore, an extensive study on comprehensive risk management for H2 ports, considering financial, operational, environmental, and reputational, is suggested. It will provide useful information for industry decision-makers in developing H2 ports.

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Appendix

Appendix: Survey Questionnaire

AMC KOBE UNIVERSITY LIVERPOOL JOHN MOORES UNIVERSITY

Hydrogen Ports: Readiness and Operational Risks

* Required

The survey aims to seek your perspective on green hydrogen logistics management (including its derivatives) and application at ports, focusing on:
- Requirement of Infrastructure and facilities
- Operational risk assessment
- Critical factors for a safe, efficient and effective hydrogen port

The term 'hydrogen port' used in this research refers to ports managing green hydrogen (and its derivates) logistics and applying hydrogen technology to power port assets.

This anonymous survey will take about 10-15 minutes to complete. Please click the '**Next**' button to commence the survey. You give consent for participating in this research by completing and submitting the survey responses.

Information of Participant

1. Which country are you based in? *

◯ Australia
◯ Japan
◯ The UK
◯ Other

2. Please indicate which state/territory of Australia you are located in.

◯ New South Wales
◯ Victoria
◯ Queensland
◯ South Australia
◯ Western Australia
◯ Tasmania
◯ Northern Territory
◯ Australian Capital Territory

3. Please indicate which territory of Japan you are located in.

◯ Hokkaido
◯ Honshu
◯ Shikoku
◯ Kyushu
◯ Other

4. Please indicate which region of the UK you are located in.

◯ South East
◯ London
◯ North West
◯ East of England
◯ West Midlands
◯ South West
◯ Yorkshire and the Humber
◯ East Midlands
◯ North East
◯ Other

5. Please indicate your professional field in the hydrogen (and its derivates) supply chain. **[Multiple choice]**

☐ Port/terminal operator
☐ Port company/authority
☐ Producer
☐ Exporter
☐ Importer
☐ Other

6. Please identify your role in the organisation.

◯ Chief executive officer
◯ Chief operating officer
◯ General operating manager
◯ Safety and health manager
◯ Manager
◯ Other

7. Please indicate the year of your service time in the relevant professional areas.
   - ◯ ≥ 30 years
   - ◯ 20 - 29 years
   - ◯ 10 - 19 years
   - ◯ < 10 years

Hydrogen forms for trade and utilisation

The following questions are about the forms of hydrogen for international trade.

8. What type of trade will you manage logistics activities of hydrogen and/or its derivatives through ports?
   - ◯ Import
   - ◯ Export
   - ◯ Both
   - ◯ Not applicable

9. Which form(s) of hydrogen will you be producing or exporting/importing? **[Multiple choice]**
   - ☐ Compressed hydrogen (CH2)
   - ☐ Liquid hydrogen (LH2)
   - ☐ Ammonia
   - ☐ Methanol
   - ☐ Liquid organic hydrogen carriers (LOHCs)
   - ☐ Not applicable
   - ☐ Other

10. Please rank the following forms of hydrogen in terms of their suitability for international trade in a 10-year timeframe, **from the highest to the lowest possibility.**
    Instruction: you can just drag and drop each choice to reorder it.
    - Compressed hydrogen (CH2)
    - Liquid hydrogen (LH2)
    - Ammonia
    - Methanol
    - Liquid organic hydrogen carriers (LOHCs)

11. Will you decarbonise your port assets by utilising hydrogen and/or its derivatives?
    - ◯ Yes
    - ◯ No
    - ◯ Maybe
    - ◯ Not applicable

12. What type of your assets will be decarbonised using hydrogen and/or its derivitaves? **[Multiple choice]**
    - ☐ Prime movers
    - ☐ Yard trucks
    - ☐ Forklifts
    - ☐ Container movers/ Reach stackers
    - ☐ Gantry cranes
    - ☐ Tug boats
    - ☐ Pilot boats
    - ☐ Harbour craft
    - ☐ Bunker barge
    - ☐ Other

13. Could you please provide additional information on why you won't decarbonise the port assets using hydrogen and/or its derivatives?

14. Will you consider providing hydrogen (and/or its derivatives) bunkering/refueling capability in ports?

- ◯ Yes
- ◯ No
- ◯ Maybe
- ◯ Not applicable

15. Which hydrogen based-fuel bunkering capacity/capacities do you consider providing? **[Multiple choice]**

- ☐ Compressed hydrogen (CH2)
- ☐ Liquid hydrogen (LH2)
- ☐ Ammonia
- ☐ Methanol
- ☐ Other

16. could you please provide additional information on why you won't consider providing hydrogen (and/or its derivatives) bunkering/refueling capability in ports.

Infrastructure sufficiency

The following questions list port infrastructure and facilities that might be required for a port in exporting or importing hydrogen (and/or its derivatives). Please indicate what are required for your port/project and then rank the sufficiency level **[from 1 (the lowest) to 9 (the highest)]** of each.

Scales for sufficiency:
1: Nonexistent; 3: Inadequate; 5: Acceptable; 7: Adequate; 9: Satisfactory

17. Please indicate what port infrastructure and facilities are required in your port/project in exporting or importing hydrogen (and/or its derivatives). **[Multiple choice]**

- ☐ Storage tanks
- ☐ Pipelines (normal temperature)
- ☐ Pipelines (cryogenic/low temperature)
- ☐ Berths
- ☐ Loading/Unloading facilities
- ☐ Liquification facilities
- ☐ Regasification facilities
- ☐ Dehydrogenation facilities
- ☐ Safety equipment
- ☐ Monitoring and control systems
- ☐ Other

18. Storage tanks: sufficiency level
Please ignore this item if it is not required in your port/project.

1	2	3	4	5	6	7	8	9

Nonexistent Satisfactory

19. Pipelines (normal): sufficiency level
Please ignore this item if it is not required in your port/project.

1	2	3	4	5	6	7	8	9

Nonexistent Satisfactory

20. Pipelines (Cryogenic/low temperature): sufficiency level
Please ignore this item if it is not required in your port/project.

1	2	3	4	5	6	7	8	9

Nonexistent Satisfactory

21. Berths: sufficiency level
Please ignore this item if it is not required in your port/project.

1	2	3	4	5	6	7	8	9

Nonexistent Satisfactory

22. Loading/Unloading facilities: sufficiency level
Please ignore this item if it is not required in your port/project.

1	2	3	4	5	6	7	8	9

Nonexistent Satisfactory

23. Liquification facilities: sufficiency level
Please ignore this item if it is not required in your port/project.

1	2	3	4	5	6	7	8	9

Nonexistent Satisfactory

24. Regasification facilities: sufficiency level
Please ignore this item if it is not required in your port/project.

1	2	3	4	5	6	7	8	9

Nonexistent Satisfactory

25. Dehydrogenation facilities: sufficiency level
Please ignore this item if it is not required in your port/project.

1	2	3	4	5	6	7	8	9

Nonexistent Satisfactory

26. Safety equipment: sufficiency level

Please ignore this item if it is not required in your port/project.

1	2	3	4	5	6	7	8	9

Nonexistent — Satisfactory

27. Monitoring and control systems: sufficiency level

Please ignore this item if it is not required in your port/project.

1	2	3	4	5	6	7	8	9

Nonexistent — Satisfactory

28. Please indicate other infrastructure and facilities are required in your port/project and rank their sufficiency levels **[from 1 (the lowest) to 9 (the highest)]**.

Berth utilisation

29. When handling hydrogen and/or its derivatives through ports, which of the following berth utilisation do you prefer?

- ◯ Common use berth
- ◯ Dedicated berth

30. Please provide any further comments with regard to your preference of berth utilisation

Readiness levels of critical factors for an efficient and effective hydrogen port

The following questions list factors that are deemed critical for an efficient and effective hydrogen port. Please consider the readiness and rank **[from 1 (the lowest) to 9 (the highest)]** of each in your port/project in managing hydrogen (and/or its derivates) logistics and applying hydrogen-related technologies to power port assets.

Scales for readiness levels:
1: Idea; 3: Actionable plan; 5: Development; 7: Validation/Demonstration; 9: Ready for extensive implementation

31. Regulations and standards

1	2	3	4	5	6	7	8	9

32. Infrastructure

1	2	3	4	5	6	7	8	9

33. Safety measures

1	2	3	4	5	6	7	8	9

34. Personnel training

1	2	3	4	5	6	7	8	9

35. Government supports

1	2	3	4	5	6	7	8	9

36. Are there any other critical factors for an efficient and effective hydrogen port you would like to mention? Please list them below and rank their readiness levels **[from 1 (the lowest) to 9 (the highest)]**?

Operational risks associated with hydrogen in a port

In the following sections, you are asked to provide your perspective assessment on the occurrence likelihood and severity of consequences of the identified hazardous events associated with managing logistics of large scale of hydrogen in ports.

Before answering the questions, please read below the description of linguistic scales used for assessment.

Occurrence likelihood

The scale of **1 to 5** represents different levels of the occurrence likelihood of the identified hazardous events as follows:

Occurrence likelihood
1: Very low. (Once in the life cycle of the whole sector/industry)
2: Low. (Once in the life cycle of the system in a port)
3. Medium. (Once in ten years in the system in a port)
4: High. (Once in a year in the system in a port)
5: Very high. (Once in a month in the system in a port)

45. Spills due to sabotage.

	1	2	3	4	5
Occurrence likelihood	○	○	○	○	○
Severity of consequences	○	○	○	○	○

46. Fire.

	1	2	3	4	5
Occurrence likelihood	○	○	○	○	○
Severity of consequences	○	○	○	○	○

47. Explosion.

	1	2	3	4	5
Occurrence likelihood	○	○	○	○	○
Severity of consequences	○	○	○	○	○

Risk assessment

Gaseous hydrogen

48. Leaks in equipment.

	1	2	3	4	5
Occurrence likelihood	○	○	○	○	○
Severity of consequences	○	○	○	○	○

49. Leaks in pipelines.

	1	2	3	4	5
Occurrence likelihood	○	○	○	○	○
Severity of consequences	○	○	○	○	○

50. Unintended venting.

	1	2	3	4	5
Occurrence likelihood	○	○	○	○	○
Severity of consequences	○	○	○	○	○

51. Leaks due to sabotage.

	1	2	3	4	5
Occurrence likelihood	○	○	○	○	○
Severity of consequences	○	○	○	○	○

52. Fire.

	1	2	3	4	5
Occurrence likelihood	○	○	○	○	○
Severity of consequences	○	○	○	○	○

53. Explosion.

	1	2	3	4	5
Occurrence likelihood	○	○	○	○	○
Severity of consequences	○	○	○	○	○

We truly appreciate your participation and value the contributions you've made!

Once you submit the responses, you have given consent for participating in this study.

Other comments

54. If you have other comments, please enter them below.

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