Critical Considerations for Port Selection in Hydrogen Export Projects

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Abstract

As the world moves towards a greener energy system, the hydrogen industry is seen as a promising one for the future. Transport infrastructure investments are complicated due to the many factors and changing project environment. The terminal's ideal location must maximize economic benefits while avoiding negative consequences. Developing nations find it difficult to choose a port for a hydrogen export terminal. Thus, this study addresses the key elements to consider while selecting a port for a new hydrogen export terminal.

The research uses a descriptive mixed methods approach, combining quantitative and qualitative data to evaluate the importance of factors affecting the selection of a port for a hydrogen export terminal. Primary data was collected through a poll with industry specialists, while secondary data was gathered from academic journals and industry reports. The study employed Likert-scale ratings and open-ended responses to gather qualitative data. Descriptive statistics were used to summarize the survey results. Thematic analysis was used to identify themes and patterns.

The research contributes to a better understanding of and measurement of the importance of the factors that should be taken into consideration in the port industry when choosing a port to construct a hydrogen export terminal. The research presented fourteen factors that were classified under three types of considerations: regulatory and standard considerations, port capabilities considerations, and economic and financial considerations.

Keywords:

Port, Port industry, Hydrogen industry, Hydrogen export terminal.

1. Introduction

Human-induced greenhouse gas (GHG) emissions have resulted in significant alterations to global ecosystems, including an increase in the global average temperature, modified precipitation patterns, intensified storms, diminished biodiversity, and rising sea levels (Calvin et al., 2023). Increasingly, nations are declaring the transition to more sustainable energy sources. In the transition to a more sustainable energy system, hydrogen is regarded as essential for achieving decarbonization goals (Spatolisano et al., 2023). Green hydrogen denotes hydrogen generated from renewable energy sources, devoid of greenhouse gas emissions. Color-band terminology categorizes hydrogen varieties based on production methods facilitated by contemporary technology: gray hydrogen from coal gasification, blue hydrogen from steam methane reforming, and green hydrogen from water electrolysis (Noussan et al., 2020). Although hydrogen is predominantly produced by technologies that generate substantial carbon emissions, the utilization of renewably powered electrolysis is anticipated to decrease costs and assume a more prominent role in the future (Alverà, 2021).

The prospect of maritime hydrogen transport at a levelized cost far below the 2 USD/kg benchmark presents a chance for nations with inexpensive renewable energy sources to emerge as exporters of hydrogen to the global market, thereby enhancing their primary macroeconomic indicators. Consequently, it is essential for policymakers to provide a framework that enables stakeholder intervention in the industry (D'Amore-Domenech et al., 2023).

Ports play a key role in the maritime industry (Paulauskas et al., 2023), as they serve as essential hubs in worldwide transportation networks, enabling trade and guaranteeing seamless, sustainable, and resilient operations (Edgerton, 2021; Ashrafi et al., 2020). Furthermore, the significance of ports in fostering economic growth within coastal nations is widely recognized (Puig & Darbra, 2018). Consequently, ports will be pivotal in the maritime export of green hydrogen and other hydrogen variants, particularly for developing nations.

Selecting a port for the construction of a hydrogen export terminal is a complex issue, particularly for developing nations. Consequently, this research examines the significant factors that must be considered when choosing a port for the establishment of a new hydrogen export terminal.

2. Background

GHG causes changes to ecosystems globally (Change, 2023). The rapid exhaustion of fossil fuels presents significant hurdles in meeting a substantial share of the world's increasing energy demands. The utilization of these conventional energy sources presents certain disadvantages. The primary concern is CO2 emissions and climate change (Obaidat et al., 2018). Energy demand is increasing substantially due to ongoing population increase and economic advancement. Industrialization is essential for the prosperity of every nation (Alkhalidi et al., 2019). This has prompted nations to concur on significantly decreasing GHG emissions and to sign the Paris Agreement.

In the transition to a more sustainable energy system, hydrogen is regarded as essential for achieving decarburization targets; the increasing interest in utilizing hydrogen as a clean energy source is attributed to two primary factors:

1. *Hydrogen can be utilized without direct GHG emissions,*

2. *It can be generated from various low-carbon energy sources (Spatolisano et al., 2023).*

Green hydrogen is a type of hydrogen generated from renewable energy sources that are devoid of GHG emissions. Although hydrogen is predominantly produced by technologies that generate considerable carbon emissions, it is anticipated that renewably powered electrolysis will decrease costs and assume a more substantial role in the future (Alverà, 2021). When it comes to national energy strategy, sixteen of the top twenty nations that create GHG have made hydrogen a priority (Chen et al., 2023).

Color-band terminology categorizes hydrogen varieties based on production methods facilitated by contemporary technology (Noussan et al., 2020). According to the World Energy Council report, green, pink, and yellow hydrogen are produced via electricity, while blue, turquoise, grey, brown, and black hydrogen are produced via fossil fuel. Table 1 presents Color-band terminology categorizing hydrogen types with the method of technology used in production, the source of power used for production/raw material, and the carbon footprint.

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Table 1: A spectrum of hydrogen colors.

No.	Terminology	Technology	Electricity source/Feedstock	Carbon footprint
1	Green Hydrogen	Electrolysis	Wind / Solar / Tidal / Geothermal	Minimal
2	Pink Hydrogen		Nuclear	
3	Yellow Hydrogen		Mixed-origin grid energy	Medium
4	Blue Hydrogen	Natural gas reforming + Carbon capture, utilization, and storage (CCUS) gasification + CCUS	Natural gas, coal	Low
5	Turquoise Hydrogen	Pyrolysis	Natural gas	Solid carbon
6	Grey Hydrogen	Natural gas reforming		Medium
7	Brown Hydrogen	Gasification	Brown coal	High
8	Black Hydrogen		Black coal	

Source of data World Energy Council report September 2021

Numerous studies, such as Kamiya et al. (2015), Al-Breiki and Bicer (2020), and Ishimoto et al. (2020), have endeavored to quantify the costs associated with hydrogen production and delivery to facilitate comparisons of various transportation methods. Certain research posited that the expenses associated with hydrogen infrastructure are either equivalent to those of natural gas infrastructure or marginally elevated, particularly with pipelines, as multiple studies indicated comparable to 10% increased capital expenditures (Al-Breiki & Bicer, 2020). Nonetheless, hydrogen and natural gas possess distinct qualities that necessitate varying material specifications (Wang et al., 2021). Prolonged exposure of steel to hydrogen results in embrittlement, necessitating specialized coatings and costly layers for pipelines to transport hydrogen effectively. Furthermore, current compressors utilized in natural gas pipeline networks are inadequate for hydrogen due to their low molecular weight, which may potentially result in leakage (Wang et al., 2021).

Consequently, repurposing existing natural gas pipelines is feasible; however, the associated expenditures would be substantial, ranging from 10 to 50% of the expense of constructing a new pipeline (Wang et al., 2021; Wang et al., 2020). Likewise, several studies presume that the capital costs of Liquefied Hydrogen (LH2) vessels are nearly identical to those for transporting Liquefied Natural Gas (LNG) (Al-Breiki & Bicer, 2020) despite the substantial temperature disparities at which these two gases are transported, with LH2 maintained at −253 °C and LNG at −162 °C. Estimates suggest that LH2 vessels may incur expenditures up to four times greater than those of LNG vessels (Amos, 1999). Notwithstanding the constraints identified in those studies, the expenses associated with hydrogen transportation were determined to be greater than those for natural gas, around 0.88 €/MWhH2/1000 km in contrast to 0.20 €/MWhLNG/1000 km for LNG shipping (Al-Breiki & Bicer, 2020), and 2.17–23.3 €/MWhH2/1000 km in contrast to 0.41–2.36 €/MWhNG/1000 km for the pipeline transport of natural gas (Saadi et al., 2018).

Hydrogen is regarded as a multifaceted and potent energy carrier in the decarbonization of the global economy, aimed at substituting fossil fuel consumption with renewable and sustainable technology (Judkins & O'Brien, 2019). Transporting liquid hydrogen is only viable for extensive distances when the costs of liquefaction can be distributed over that distance (Amos, 1999). An exemplary international hydrogen supply chain comprises production, conversion, storage, transportation, distribution, reconversion, and usage (James & Menzies, 2023). Figure 1 illustrates a conventional green hydrogen supply chain. Ports and shipping are essential components of the supply chain. In exporting nations, hydrogen is generated using water electrolysis utilizing renewable energy sources. The low density of gaseous hydrogen requires its transformation into alternate forms, like compressed hydrogen, LH2, or chemical carriers such as ammonia (NH3), methanol, or liquid organic hydrogen carriers, to enhance its storage and transportation efficiency. Upon its arrival at the export port, hydrogen is transported to the import port. Subsequently, it enters a distribution phase and, when necessary, undergoes reconversion operations to meet the demands of end-users, encompassing transportation (Jayakumar et al., 2022), high-temperature industrial applications, and residential usage (Xu et al., 2024; Elkhatib et al., 2024; Superchi et al., 2023). Energy conversion at the point of consumption can be accomplished by fuel cells, internal combustion engines, steam turbines, gas turbines, and burners.

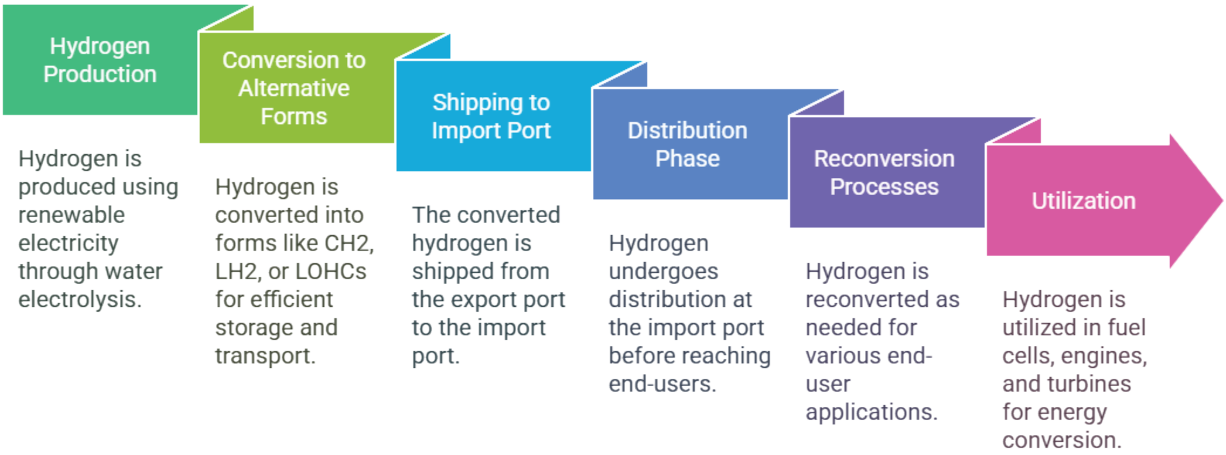

Figure 1: Conventional green hydrogen supply chain.
Source: Author (using Napkin)

The long-distance transport of hydrogen and its international export is regarded as a crucial strategy for mitigating GHG emissions and represents a substantial economic potential, leveraging enormous renewable energy supplies (Walsh et al., 2021). At the end of the year 2021, a liquid hydrogen carrier set sail from Kobe, Japan, to Australia. It arrived back in Kobe at the end of February, carrying the first cargo of its kind. At a temperature of -253 degrees Celsius, this vessel is capable of holding a volume of 1250 cubic meters of liquid hydrogen (Pekic, 2022).

The outcomes of this test shipment will undergo additional analysis and development; nonetheless, the concept is not slated to go to a commercial-stage until the mid to late 2020s. Kawasaki Heavy Industries has announced the development of a large LH2 carrier with a capacity of 160,000 m^3, anticipated to commence operations in the mid-2020s (Kawasaki Heavy Industries, 2022; Raab et al., 2021).

As hydrogen demand escalates, enhanced capacity connecting additional regions will be required for its transportation. The capital expenditures for pipelines are substantial, and it is probable that cryogenic vessels onboard ships for the transport of liquid hydrogen, together with the liquefaction process, will continue to be costly, particularly in the initial phases (Aghakhani et al., 2023). However, scientists and researchers are working on cost reduction as well as any other technologies that provide the chance for production on a large scale, especially for the developing countries that possess a wealth of land and renewable energy resources that facilitate the production of green hydrogen. As a result, the necessitating establishment of export terminals in ports.

Investments in transport infrastructure are inherently complex due to the multitude of influencing aspects and the evolving environment in which projects are executed. Establishing the terminal's best location is crucial to maximize economic benefits while minimizing adverse effects. The establishment of gas terminals is a substantial economic endeavor. It harnesses spatial and economic potentials in accordance with the intended use of the premises, environmental and security regulations, as well as the availability of infrastructure and other essential components for the terminal's operation without substantially adversely affecting individuals and the environment (Krpan et al., 2023).

3. Methodology

The methodology in this research assigned a descriptive mixed methods approach that combines quantitative and qualitative data collection to evaluate and compare the significance of diverse criteria affecting the choice of a port for the establishment of a hydrogen export terminal. A poll was performed with industry specialists from the maritime industry and hydrogen industry to collect primary data using purposive sampling. Engaging with these professionals seeks to acquire useful insights into the current burgeoning hydrogen industry as an energy source.

The questionnaire was piloted with a group of six maritime PhD holders, three of whom are research reviewers. The questionnaire was tested to enhance its quality and check validity and reliability. To furnish a questionnaire with eight questions pertaining to participant data and 27 questions relevant to the research issue. The questionnaire was revised and retested for the same group based on the input received.

Alongside primary data collecting, secondary data is obtained from academic journals, industry reports, and pertinent publications. This secondary data will offer a solid basis of existing information, research outcomes, and theoretical frameworks pertinent to the hydrogen

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and maritime industries. By synthesizing both primary and secondary data, we can provide a thorough overview of the subject.

Quantitative using Likert-scale ratings that comprise a declaration or inquiry by a sequence of five response sentences. Participants select the choice that most accurately reflects their sentiments toward the statement or inquiry. Qualitative using open-ended responses that Facilitate a thorough and comprehensive examination of the examined issues since open-ended comments enable respondents to offer a broader range of ideas and perspectives. This method entails the methodical organization and categorization of data to discern major themes and patterns, facilitating the derivation of significant conclusions. Descriptive statistics were employed to present a quantitative summary of the participants' viewpoints based on the survey results.

Thematic analysis is a form of qualitative analysis employed to examine categories and highlight themes (patterns) pertinent to the data. Thematic analysis denotes a method of pattern recognition that entails identifying fundamental themes (specifically, 'theories' or 'approaches') by meticulous reading and re-reading of the material (Javadi & Zarea, 2016). Therefore, the method assigned as a qualitative analysis method for questionnaire designing and the analyses of open-ended questions through 5 steps:

1. **Familiarization:** obtain a comprehensive understanding of all the obtained data prior to commencing the analysis of individual items.

2. **Coding:** involves identifying segments of text, typically phrases or sentences, and assigning concise "codes" to encapsulate their meaning.

3. **Generating themes:** Examine the labels or codes developed, discern patterns within them, and begin formulating themes. Themes typically encompass a greater scope than decarbonization codes.

4. **Evaluate themes:** ensure that themes provide meaningful and precise representations of the data.

5. **Naming and defining themes.**

Throughout the research procedure, the author adheres to ethical principles by obtaining informed consent from participants and assuring the maintenance of their privacy and confidentiality. Recognize the constraints of the research, including possible participant availability and the subjective analysis of qualitative data. Nevertheless, the Author is dedicated to meticulously undertaking this study to enhance the current body of information regarding hydrogen and the port industry.

4. Sampling and papulation

The research assigned purposive sampling to obtain representative samples. where participants are chosen based on their active participation and experience in maritime, port and hydrogen industrial sectors, table 2 present targeted stakeholders and their role in the industry and the rationale behind the choice.

The data were collected through a questionnaire that distrebuted online giving the particepent from 2 to 4 weeks to resond, ferthermore, respondes were anonymized for the purpose of confidentiality ensure. The questionnaire was distributed to 67 targeted stakeholders. The final total number of responses for the sample is 28 responses.

Table 2: Targeted Stakeholders.

No.	Stakeholders	Stakeholders role	Rationale
1	Port Authorities and Managers	Decision-making is overseeing port operations, development, and infrastructure (Saieva, 2013; De Martino, 2014).	Comprehend the port's current infrastructure, operational difficulties, capacity, and prospects for expansion (Saieva, 2013; De Martino, 2014).
2	Engineers and Technical Experts	Engaged in the design, construction, and maintenance of hydrogen infrastructure, including storage, pipelines, and liquefaction/ compression facilities (Hao et al., 2024).	Can offer insights into technical feasibility, safety, and the compatibility of existing port infrastructure with hydrogen specifications (Hao et al., 2024).
3	Renewable Energy Producers	Engaged in renewable energy production (solar, wind, hydro) that could provide power for hydrogen generation (Benghanem et al., 2023).	Their contributions are critical for evaluating the availability and dependability of renewable energy required for green hydrogen production through electrolysis (Benghanem et al., 2023).
4	Hydrogen Industry Specialists	Specialists in hydrogen generation, storage, and transportation technologies, especially those from firms focused on green hydrogen development (Hao et al., 2024).	They possess extensive expertise in the specific needs for the safe and effective handling and exportation of hydrogen (Hao et al., 2024).

5	Environmental Experts and Regulators	Environmental scientists, sustainability specialists, and officials from regulatory agencies dedicated to environmental protection and climate change mitigation (Islam et al., 2024; Sharma et al., 2024).	They offer insights into the environmental implications of hydrogen production and export, encompassing legislation, environmental hazards, and sustainability considerations (Islam et al., 2024; Sharma et al., 2024).
6	Economists and Financial Analysts	Economists, financial analysts, and project finance specialists concentrate on substantial infrastructure initiatives.	Their proficiency is essential for evaluating the financial feasibility, long-term return on investment (ROI), and economic implications of the hydrogen export terminal (Ives, 2016).
7	Policy Makers and Government Officials	Government officials engaged in energy policy, infrastructure development, and environmental regulation (Islam et al., 2024).	They can provide insights into national energy strategies, regulatory frameworks, and governmental incentives that may impact the establishment of green hydrogen terminals (Islam et al., 2024).
8	Shipping and Logistics Companies	Representatives from maritime shipping businesses and logistics enterprises responsible for the transportation of products, particularly hazardous items, by sea.	Their experience is essential for assessing the port's capability to manage hydrogen exports and incorporate them into international shipping routes.
9	Safety and Risk Management Experts	Safety officers and specialists in risk management, particularly concerning flammable and dangerous substances such as hydrogen.	They are capable of evaluating safety protocols, emergency response plans, and risk management strategies necessary for the storage, transportation, and exportation of hydrogen (Froufe et al., 2014).
10	Industrial Hydrogen Consumers	Representatives from sectors that may potentially utilize green hydrogen, such as steel manufacturing, chemical industries, and transportation.	Their insights regarding supply chain reliability and hydrogen demand are crucial for ensuring the terminal meets market requirements.
11	Community Stakeholders	Representatives from local communities, environmental non-governmental organizations, and other NGOs focused on sustainability and community effects.	Community feedback is essential for comprehending public sentiment, assessing potential social ramifications, and ensuring the project is congruent with local sustainability objectives.
12	Academia and Research Institutions	Researchers and academics specializing in researching renewable energy, hydrogen technology, environmental science, or port logistics.	Their insights on long-term sustainability, technological advancements, and scholarly research can guide strategic decisions and innovations for the project (Diaconu & Salaj, 2024).
13	International Energy and Trade Organizations	Delegates from entities such as the International Energy Agency (IEA) or the International Maritime Organization (IMO).	Provide insights into global energy trends, forecasts for hydrogen demand, and international rules concerning energy transition and hydrogen commerce.
14	Investors and Private Sector Stakeholders	Institutional investors, venture capitalists, or private enterprises seeking to invest in renewable energy or hydrogen infrastructure.	Their involvement is essential for comprehending financial viability and obtaining funding for sustained development.
15	Legal and Compliance Experts	Legal consultants with expertise in energy law, maritime law, and environmental legislation.	Their contributions guarantee compliance with all legal and regulatory requirements throughout the planning and implementation stages (Islam et al., 2024; Sharma et al., 2024).
16	Labor Unions and Workforce Representatives	Advocates for laborers at the port or associated sectors.	Crucial for tackling personnel preparedness, training requirements, and labor regulations concerning hydrogen exports.

Source: Author

Samples were collected from targeted stakeholders from several nations, including China, Egypt, Japan, Jordan, Nigeria, Saudi Arabia, Sweden, Tunisia, and Uganda. Simultaneously, the sample, as shown in Figure 2 as a percentage, includes 28 responses from the targeted stockholders presented in Table 2, except labor unions and workforce representatives, who did not respond.

Figure 2: Percentage of stakeholder participation in the survey.
Source: Author (using Microsoft Excel)

5. Analysis, Results, and Discussion

5.1. Data analysis methods

Regarding Quantitative Analysis using "Likert Scale Responses," This phase of the study will focus on the number of responses for each element, utilizing the Likert scale (1–5) from the questionnaire. First, the author computed the mean score for each question by summing up the respondents' ratings and dividing them by the total number of responses using the following formula. $Mean\ Score = \frac{\Sigma(All\ Ratings)}{Number\ of\ Respondents}$ This will assist in comprehending the perceived weight of each element. Secondly, the author delineated the high and low-priority variables, with high-priority components exhibiting mean scores near 5, whereas low-priority factors displayed mean scores approaching 1 or 2, indicating lesser significance. Thirdly, the author calculated the Standard Deviation for each question for the purpose of measuring the variability of each question using the formula $SD = \frac{\sqrt[2]{\Sigma(Rating-Mean\ Score)2}}{Number\ of\ Respondents}$ where A low standard deviation indicates consensus among respondents on the component's relevance, while a high standard deviation reflects divergent viewpoints.

Regarding Qualitative analysis of open-ended responses, the respondents' comments and explanations can provide a more comprehensive knowledge of the factors influencing the high or low ratings of specific aspects. The initial phase uses thematic analysis by Highlighting significant themes that emerge in the comments. Consolidate similar responses to identify prevalent issues or suggestions. Followed by Theme Frequency through enumerating the occurrences of each theme after categorizing the comments accordingly. This can facilitate the ranking of difficulties or options that responders most frequently cited, followed by evaluating the comments, whether they express positive, neutral, or negative opinions toward a specific element.

5.2. Results

In accordance with the methodology employed in this research, as shown in Figure 3, the survey results from the questionnaire revealed that the mean scores of the criteria ranged from 4.16 to 3.69 out of 5, indicating that these factors are of high priority. The standard deviation ranges from 1.12 to 1.28, which is seen as low, indicating a consensus among respondents about the factors. The factors are listed below in descending order of importance based on the survey analysis completed.

1. **Operational and Safety Challenges:** indicated as the highest important factor where the importance of chosen port's safety infrastructure and protocols combined with the availability of qualified personals and experts to manage operations related to hydrogen specifically.

2. **Environmental Impact & Regulations:** indicated as the second highest important factor where the importance of the chosen port's ability to comply with environmental regulations for hydrogen production and export, conversely with the capability of the port to handle environmental risks as hydrogen leak and marine impacts.

3. **Logistics & Connectivity:** appeared as the third factor in respect of importance where the importance of the chosen port's connectivity with inland transport systems as rail, road, and pipelines for supplying hydrogen, furthermore, the ability to develop bunkering infrastructure for hydrogen and other renewable fuels.

4. **Risk Management & Safety Protocols:** where the importance of the chosen port's ability to respond to emergencies or accidents involving hydrogen, handle and manage hydrogen-specific risks as leaks and explosions through established safety protocols.

5. **Energy Supply & Integration:** where the importance of the chosen port's crucial factor is the proximity of renewable energy sources to the port, such as offshore wind farms or solar plants, to facilitate electrolysis—the production of hydrogen.

6. **Port accessibility & geographical location:** where the chosen port should be close to the main shipping leans accessing the hydrogen market, moreover, the port should be close to the hydrogen production facilities.

7. **Technological Innovation in Hydrogen Handling:** where the chosen port supported with the availability of advanced technologies regarding hydrogen storage, transport, and safety in addition to the presence of potential for the adoption of automated/digitalized operations for hydrogen export management.

8. **Costs & Financial Viability:** where the chosen port must possess the capacity to secure the requisite initial investments for hydrogen-specific infrastructure through self-funding, governmental help, private investors, or a combination thereof, considering the long-term return on investment (ROI).

9. **Hydrogen Supply Chain Economics:** where the selected port must optimize costs along the hydrogen supply chain, from manufacturing to export.

10. **Hydrogen Handling Infrastructure:** the chosen port must equilibrium between available infrastructure, such as pipelines and storage tanks and, the adoption or expiation for the infrastructure to export hydrogen efficiently and safely.

11. **Energy Transition & Policy Support:** the chosen port's ability to apply the needed alignment with the national and international energy transition policies regarding the port's hydrogen terminal and utilizing government incentives or subsidies for hydrogen industry development.

12. **Market Demand & Supply Chain:** where the importance of the port's ability to integrate with global alliances for hydrogen supply and logistical networks with the proximity to major hydrogen markets in Europe and, Asia.

13. **Stakeholder Collaboration:** The importance of the port's capability to facilitate hydrogen export through collaboration with key stakeholders, including governmental entities, renewable energy providers, and logistics firms.

14. **Port Throughput & Capacity:** The importance of the port's capability to handle substantial hydrogen exports, encompassing storage and loading facilities, together with prospective developments to accommodate the increasing demand for hydrogen exports.

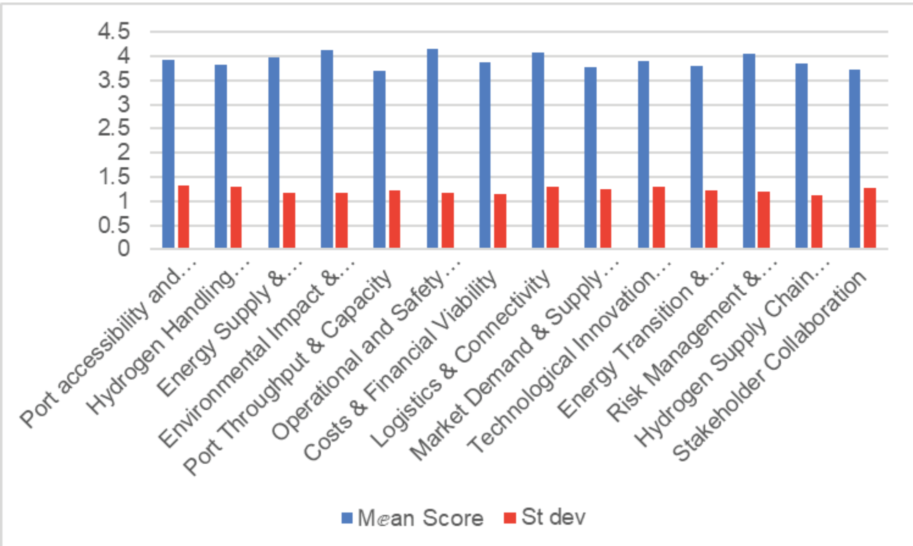

Figure 3: Mean Score and Standard Deviation for the Questionnaire Output.
Source: Author (using Microsoft Excel)

In addition to the above-mentioned factors, shipping and logistics companies' stakeholders, as well as safety and risk management experts, indicated that clarification on the enforcement of safety regulations pertaining to the handling of liquid or compressed hydrogen is required. Port tariffs, docking fees, and operational expenses must remain competitive to provide economical hydrogen transportation. The terminal's operating efficiency, encompassing loading and unloading speed, will influence shipping schedules and expenses. Hydrogen loading infrastructure must reduce delays and synchronize with stringent shipping schedules.

Port Authorities, Managers, experts, and stakeholders indicated that the port must provide deep-water access and sufficient berth capacity to accommodate specialized hydrogen vessels. An evaluation of the current port infrastructure is required to ascertain the feasibility of improvements for hydrogen storage and loading facilities.

Economists and financial analysts indicated that analyzing the trials of industry comparators and monitoring the industry's pressure points may conserve time and lives. In other words, it commences from the conclusions of others.

Academia and Research Institutions, Investors, and Private Sector Stakeholders indicated that The port must possess comprehensive hydrogen storage facilities, infrastructure for effective hydrogen liquefaction or conversion, and a dependable pipeline or trucking system for transferring hydrogen from producing sites to the port. An uninterrupted supply chain with few impediments will diminish operational delays and expenses. The port must possess the capacity for expansion to accommodate the increasing worldwide demand for hydrogen and have a flexible infrastructure capable of incorporating novel hydrogen carriers and technologies.

While Industrial Hydrogen Consumers said, *"We are giving more attention to the green hydrogen."*

5.3. Discussion

Hydrogen serves as an exceptional energy carrier due to its elevated energy density (Gretz et al., 1994). LH2, in contrast to NH3 and liquid organic hydrogen carriers (LOHC), does not necessitate supplementary energy for dehydrogenation or cracking upon importation and exhibits a greater mass density (70 kg/m3) than compressed gaseous hydrogen (Ratnakar et al., 2021). Thus, LH2 is among the most appropriate options for intercontinental renewable energy transfer (Notardonato et al., 2017).

Maritime shipping primarily facilitates large-scale transportation. Maritime shipping is vital, particularly for transcontinental or long-distance transport. The maritime supply chain includes renewable energy generation, hydrogen production, hydrogen liquefaction, export terminals, tankers, import ports, and utilization. Ports serve as a critical node and connections within the supply chain and can function as a central hub for the hydrogen sector from production to consumption (Kim et al., 2024; Hong et al., 2021; Roos, 2021). Ports are advantageous sites for hydrogen production if they are proximate to renewable energy sources, enhance hydrogen transport logistics for both export and import, and utilize hydrogen as an energy source for the ports' assets, including vehicles, machines, and vessels (Fan et al., 2024; Guan et al., 2023; Chang et al., 2019). Fages et al. forecasted that green hydrogen will decarbonize ports and adjacent businesses, resulting in the development of new port infrastructure for hydrogen production and refueling in the forthcoming years (Fages et al., 2023).

Deloitte's extensive analysis forecasts possible demand for as much as 42% (22 million tons) of the EU's hydrogen consumption in 2050 in European ports and coastal regions (Deloitte, 2023). Conversely, Japan revised its hydrogen policy to prioritize the development of hydrogen demand across all economic sectors and the importation of hydrogen from overseas (REI, 2022). The ports' preparedness for worldwide hydrogen trade is nascent. Infrastructure construction or refurbishment, risk management strategies, the formulation of rules and standards, and education and training necessitate increased resources (Chen et al., 2023).

The research results can be divided into three main findings, which are: regulatory and standard considerations, port capabilities considerations and, economic and financial considerations, and these findings are discussed below.

Regulatory and standard considerations:

Regulatory and standard considerations include factors 1, 2, 4, and 11, where the research findings indicate that terminal safety protocols and operational safety challenges are critical due to hydrogen's flammability. Consequently, qualified personnel and experts, in addition to education and training, necessitate increased resources to implement the appropriate protocols and navigate the operational safety challenges effectively. The management of risks associated with the capacity to respond to emergencies or accidents involving hydrogen, as well as the handling and mitigation of hydrogen-specific hazards such as leaks and explosions, emerged as the fourth component, while both factors exhibit a strong correlation concerning adaptation. Both factors were discussed by Chen et al. (2024), Peace et al. (2023), and Lanphen (2019) in their studies.

The compliment with environmental regulations for hydrogen production and export, conversely with the capability of the port to handle environmental risks to comply with as hydrogen leak and marine impacts came as the second import factor which was were discussed by Chen et al. (2024), Peace et al. (2023) and Lanphen, (2019) in their studies. The 11th factor addressed the port's capacity to connect with national and international energy transition strategies concerning its hydrogen terminal and to leverage government incentives or subsidies for the advancement of the hydrogen industry.

Port capabilities considerations:

Port capabilities include factors 3, 5, 6, 7, 10, and 14, where the chosen port should be distinguished by logistical connectivity with inland transportation systems such as rail, road, and pipelines for hydrogen delivery, as well as the capacity to provide bunkering infrastructure for hydrogen and other renewable fuels. Along with energy supply integration, where the port should be close to the hydrogen production facilities, and the closeness of renewable energy sources, such as offshore wind farms or solar plants, to the port is intended to enable electrolysis, the process of green hydrogen production. Furthermore, the importance of port accessibility and geographical location where the closeness to main shipping leans accessing the hydrogen market, as indicated by Chen et al. (2024), Semchukova et al. (2024), Peace et al. (2023) and Lanphen (2019) in their researches.

Complying with Semchukova et al. (2024, Brauer et al. (2022), and Lanphen (2019), the chosen port should be distinguished by sophisticated technology for hydrogen storage, transportation, and safety, as well as the capability for implementing automated and digitalized processes for hydrogen export management, in addition to hydrogen handling infrastructure that is essential for balancing existing facilities, such as pipelines and storage tanks, with the development or expansion of infrastructure necessary for the efficient and safe export of hydrogen and, port efficiency presented in port throughput and capacity.

Economic and financial considerations:

Economic and financial considerations include factors 8, 9, 12, and 13, where the chosen port should be distinguished by the capability to obtain the necessary initial investments for hydrogen-specific infrastructure through self-financing, government assistance, private investors, or a mix of these while taking into account the long-term return on investment (ROI).

The economics of the hydrogen supply chain need the chosen port to optimize expenses across the entire process, from production to exportation. Market demand and supply chain emphasize the significance of the port's capacity to integrate with global hydrogen supply alliances and logistical networks, given its closeness to major hydrogen markets in Europe and Asia. In addition, Collaboration among stakeholders emphasizes the port's capacity to enable hydrogen export through partnerships with essential organizations, including governmental bodies, renewable energy suppliers, and logistics companies.

Finally, for the purpose of validation regarding the results and findings, table 3 is showing the factors consistent and agreement with the literature.

Table 3: Compatibility between results, findings, and sources of literature.

Finding	Factor	Source	Author
Regulatory and standard considerations	Operational and Safety Challenges	Hydrogen, Volume 5 (2024)	(Chen et al., 2024)
		ADIPEC Conference, Abu Dhabi, United Arab Emirates	(Peace et al., 2023)
		MSc thesis thesis, Delft University of Technology	(Lanphen, 2019)
	Environmental Impact & Regulations	Hydrogen, Volume 5 (2024)	(Chen et al., 2024)
		The National Renewable Energy Laboratory (NREL)	(Semchukova et al., 2024)
		ADIPEC Conference, Abu Dhabi, United Arab Emirates	(Peace et al., 2023)
		MSc thesis, Delft University of Technology	(Lanphen, 2019)
	Risk Management & Safety Protocols	Hydrogen, Volume 5 (2024)	(Chen et al., 2024)
		ADIPEC Conference, Abu Dhabi, United Arab Emirates	(Peace et al., 2023)
		M.Sc. thesis, Delft University of Technology	(Lanphen, 2019)
	Energy Transition & Policy Support	M.Sc. thesis, Delft University of Technology	(Lanphen, 2019)

Port capabilities considerations	Logistics & Connectivity	Hydrogen, Volume 5 (2024)	(Chen et al., 2024)
		The National Renewable Energy Laboratory (NREL)	(Semchukova et al., 2024)
		M.Sc. thesis, Delft University of Technology	(Lanphen, 2019)
	Energy Supply & Integration	The National Renewable Energy Laboratory (NREL)	(Semchukova et al., 2024)
		18th International Conference on the European Energy Market (EEM)	(Brauer et al., 2022)
	Port accessibility and geographical location	The National Renewable Energy Laboratory (NREL)	(Semchukova et al., 2024)
		M.Sc. thesis, Delft University of Technology	(Lanphen, 2019)
	Technological Innovation in Hydrogen Handling	Hydrogen, Volume 5 (2024)	(Chen et al., 2024)
		The National Renewable Energy Laboratory (NREL)	(Semchukova et al., 2024)
		ADIPEC Conference, Abu Dhabi, United Arab Emirates	(Peace et al., 2023)
		18th International Conference on the European Energy Market (EEM)	(Brauer et al., 2022)
	Hydrogen Handling Infrastructure	Hydrogen, Volume 5 (2024)	(Chen et al., 2024)
		The National Renewable Energy Laboratory (NREL)	(Semchukova et al., 2024)
		18th International Conference on the European Energy Market (EEM)	(Brauer et al., 2022)
		18th International Conference on the European Energy Market (EEM)	(Brauer et al., 2022)
	Port Throughput & Capacity	18th International Conference on the European Energy Market (EEM)	(Brauer et al., 2022)
Economic and financial considerations	Costs & Financial Viability	The National Renewable Energy Laboratory (NREL)	(Semchukova et al., 2024)
		ADIPEC Conference, Abu Dhabi, United Arab Emirates	(Peace et al., 2023)
		18th International Conference on the European Energy Market (EEM)	(Brauer et al., 2022)
		M.Sc. thesis, Delft University of Technology	(Lanphen, 2019)
	Hydrogen Supply Chain Economics	ADIPEC Conference, Abu Dhabi, United Arab Emirates	(Peace et al., 2023)
		18th International Conference on the European Energy Market (EEM)	(Brauer et al., 2022)
	Market Demand & Supply Chain	Hydrogen, Volume 5 (2024)	(Chen et al., 2024)
		M.Sc. thesis, Delft University of Technology	(Lanphen, 2019)
	Stakeholder Collaboration	18th International Conference on the European Energy Market (EEM)	(Brauer et al., 2022)

Source: Author

Key stakeholders maintain a strong emphasis on the prioritization of implementing standards and regulations, particularly with safety and environmental issues, as these variables significantly influence the terminal project from the design phase through to operation. The secondary goal for the principal stakeholder in port capabilities is to facilitate the adoption of standards and regulations, as well as to address economic and financial concerns that ensure project funding and guarantee project ROI.

The study employed a limited sample of 28 participants and a small number of variables via a questionnaire, which represents a research limitation, particularly for an emerging sector such as the hydrogen business. Consequently, it is advisable to do additional studies utilizing a larger sample through interviews and questionnaires that incorporate a broader range of variables.

6. Conclusion

The research provided a comprehensive evaluation of 14 critical factors that influence the port selection to develop a hydrogen export terminal. Challenges of operation and safety, regulatory compliance, environmental impact, and port logistics connectivity are highlighted in the findings as the stakeholders' highest priority. These factors underscore the significance of robust safety systems, qualified staff, and stringent compliance with environmental regulations in the management of hydrogen-related processes. Moreover, stakeholders emphasized port capabilities, including port accessibility and geographic location, hydrogen handling technology, access to renewable energy resources, and needed infrastructure. These capabilities support the port effectively from production to export. Furthermore, the research highlights the importance of investment capability and integration with the global market supply chain to ensure economic and financial viability. Key stakeholders confirm a growing general agreement on the essential requirement of port modernization to accommodate a hydrogen export terminal.

References

Aghakhani, A. *et al.* (2024) 'Hydrogen transportation and distribution', in *Towards Hydrogen Infrastructure*. Elsevier, pp. 187–224. Available at: https://doi.org/10.1016/B978-0-323-95553-9.00003-0.

Al-Breiki, M. and Bicer, Y. (2020) 'Comparative cost assessment of sustainable energy carriers produced from natural gas accounting for boil-off gas and social cost of carbon', *Energy Reports*, 6, pp. 1897–1909. Available at: https://doi.org/10.1016/j.egyr.2020.07.013.

Alkhalidi, A., Khawaja, M.K. and Abusubaih, D. (2020) 'Energy efficient cooling and heating of aquaponics facilities based on regional climate', *International Journal of Low-Carbon Technologies*, 15(2), pp. 287–298. Available at: https://doi.org/10.1093/ijlct/ctz053.

Amos, W.A. (1999) *Costs of Storing and Transporting Hydrogen*. Golden, CO (United States). Available at: https://doi.org/10.2172/6574.

Ariful Islam, Md. *et al.* (2025) 'Mitigation of environmental impacts and challenges during hydrogen production', *Bioresource Technology*, 415, p. 131666. Available at: https://doi.org/10.1016/j.biortech.2024.131666.

Ashrafi, M. *et al.* (2020) 'A review of corporate sustainability drivers in maritime ports: a multi-stakeholder perspective', *Maritime Policy & Management*, 47(8), pp. 1027–1044. Available at: https://doi.org/10.1080/03088839.2020.1736354.

Benghanem, M. *et al.* (2023) 'Hydrogen Production Methods Based on Solar and Wind Energy: A Review', *Energies*, 16(2), p. 757. Available at: https://doi.org/10.3390/en16020757.

Brauer, J., Truby, J. and Villavicencio, M. (2022) 'Establishing low-carbon hydrogen trade relations - where to go and who to partner with?', in *2022 18th International Conference on the European Energy Market (EEM)*. IEEE, pp. 1–6. Available at: https://doi.org/10.1109/EEM54602.2022.9921065.

Calvin, K. *et al.* (2023) *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland*. Available at: https://doi.org/10.59327/IPCC/AR6-9789291691647.

Chang, C.-C., Huang, P.-C. and Tu, J.-S. (2019) 'Life cycle assessment of yard tractors using hydrogen fuel at the Port of Kaohsiung, Taiwan', *Energy*, 189, p. 116222. Available at: https://doi.org/10.1016/j.energy.2019.116222.

Chen, P.S.-L. *et al.* (2023) 'A review on ports' readiness to facilitate international hydrogen trade', *International Journal of Hydrogen Energy*, 48(46), pp. 17351–17369. Available at: https://doi.org/10.1016/j.ijhydene.2023.01.220.

Chen, P.S.-L. *et al.* (2024) 'Opportunities and Challenges of Hydrogen Ports: An Empirical Study in Australia and Japan', *Hydrogen*, 5(3), pp. 436–458. Available at: https://doi.org/10.3390/hydrogen5030025.

d'Amore-Domenech, R. *et al.* (2023) 'On the bulk transport of green hydrogen at sea: Comparison between submarine pipeline and compressed and liquefied transport by ship', *Energy*, 267, p. 126621. Available at: https://doi.org/10.1016/j.energy.2023.126621.

Deloitte (2023) 'Study on hydrogen in ports and industrial coastal areas – Reports'. Available at: https://www.clean-hydrogen.europa.eu/media/publications/study-hydrogen-ports-and-industrial-coastal-areas-reports_en.

Diaconu, M.G. and Temeljotov Salaj, A. (2024) 'Enhancing Innovation in Higher Education Institutions: Barriers, Actions and Strategic Instruments for Sustainable Innovation', *European Conference on Innovation and Entrepreneurship*, 19(1), pp. 148–157. Available at: https://doi.org/10.34190/ecie.19.1.2619.

Edgerton, M. (2021) 'Port and Maritime Security and Sustainability', in, pp. 155–167. Available at: https://doi.org/10.1007/978-3-030-69325-1_8.

Elkhatib, R., Kaoutari, T. and Louahlia, H. (2024) 'Green hydrogen energy source for a residential fuel cell micro-combined heat and power', *Applied Thermal Engineering*, 248, p. 123194. Available at: https://doi.org/10.1016/j.applthermaleng.2024.123194.

Fages, E. *et al.* (2024) 'Ports and green hydrogen: Match made in heaven?' Roland Berger GmbH. Available at: https://www.rolandberger.com/en/Insights/Publications/Ports-and-green-hydrogen-Match-made-in-heaven.html.

Fan, H. *et al.* (2024) 'Comparative study of LNG, liquid hydrogen, and liquid ammonia post-release evaporation and dispersion during bunkering', *International Journal of Hydrogen Energy*, 65, pp. 526–539. Available at: https://doi.org/10.1016/j.ijhydene.2024.04.039.

GRETZ, J. *et al.* (1994) 'Status of the hydro-hydrogen pilot project (EQHHPP)', *International Journal of Hydrogen Energy*, 19(2), pp. 169–174. Available at: https://doi.org/10.1016/0360-3199(94)90123-6.

Guan, W. *et al.* (2023) 'Safe Design of a Hydrogen-Powered Ship: CFD Simulation on Hydrogen Leakage in the Fuel Cell Room', *Journal of Marine Science and Engineering*, 11(3), p. 651. Available at: https://doi.org/10.3390/jmse11030651.

Hao, G. *et al.* (2024) 'Current Status and Challenges in the Development of Hydrogen Transmission Pipeline Technology', *E3S Web of Conferences*, 598, p. 02008. Available at: https://doi.org/10.1051/e3sconf/202459802008.

Hong, X. *et al.* (2021) 'Techno-enviro-economic analyses of hydrogen supply chains with an ASEAN case study', *International Journal of Hydrogen Energy*, 46(65), pp. 32914–32928. Available at: https://doi.org/10.1016/j.ijhydene.2021.07.138.

Intergovernmental Panel on Climate Change (IPCC), Climate Change 2021 – The Physical Science Basis (2023). Cambridge University Press. Available at: https://doi.org/10.1017/9781009157896.

Ishimoto, Y. *et al.* (2020) 'Large-scale production and transport of hydrogen from Norway to Europe and Japan: Value chain analysis and comparison of liquid hydrogen and ammonia as energy carriers', *International Journal of Hydrogen Energy*, 45(58), pp. 32865–32883. Available at: https://doi.org/10.1016/j.ijhydene.2020.09.017.

Ives, M. (2020) 'Financial Statement Analysis', in *Encyclopedia of Public Administration and Public Policy, Third Edition*. Routledge, pp. 1–7. Available at: https://doi.org/10.1081/E-EPAP3-120043335.

James, N. and Menzies, M. (2023) 'Distributional Trends in the Generation and End-Use Sector of Low-Carbon Hydrogen Plants', *Hydrogen*, 4(1), pp. 174–189. Available at: https://doi.org/10.3390/hydrogen4010012.

Javadi, M. and Zarea, K. (2016) 'Understanding Thematic Analysis and its Pitfall', *Journal of Client Care*, 1(1). Available at: https://doi.org/10.15412/J.JCC.02010107.

Jayakumar, A. *et al.* (2022) 'Can hydrogen be the sustainable fuel for mobility in India in the global context?', *International Journal of Hydrogen Energy*, 47(79), pp. 33571–33596. Available at: https://doi.org/10.1016/j.ijhydene.2022.07.272.

Judkins, M. and O'Brien, J. (2019) 'Australian and Global hydrogen Demand Growth Scenario analysis.', *Deloitte* [Preprint]. Available at: https://www.dcceew.gov.au/sites/default/files/documents/nhs-australian-and-global-hydrogen-demand-growth-scenario-analysis-report-2019.pdf (Accessed: 10 May 2004).

Kamiya, S., Nishimura, M. and Harada, E. (2015) 'Study on Introduction of CO2 Free Energy to Japan with Liquid Hydrogen', *Physics Procedia*, 67, pp. 11–19. Available at: https://doi.org/10.1016/j.phpro.2015.06.004.

Kim, Jungwoog *et al.* (2024) 'Technical feasibility of large-scale transportable liquid hydrogen export terminal', *International Journal of Hydrogen Energy*, 66, pp. 499–511. Available at: https://doi.org/10.1016/j.ijhydene.2024.03.343.

Krpan, L. *et al.* (2023) 'Application of Multicriteria Analysis in the Selection of the LNG Terminal Location', *Naše more*, 70(4), pp. 210–218. Available at: https://doi.org/10.17818/NM/2023/4.3.

Lanphen, S. (2019) 'Hydrogen Import Terminal: Providing insights in the cost of supply chain elements of various hydrogen carriers for the import of hydrogen '. Available at: https://repository.tudelft.nl/islandora/object/uuid%3Ad2429b05-1881-4e42-9bb3-ed604bc15255.

De Martino, M. (2014) 'Sustainable Development Strategies of the Port Authority: The Network Approach', *Advanced Engineering Forum*, 11, pp. 87–95. Available at: https://doi.org/10.4028/www.scientific.net/AEF.11.87.

‘News & Events, Kawasaki obtains AIP for large, 160,000m3 liquefied hydrogen carrier’ (2022). Available at: https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20220422_3378.

Notardonato, W.U. *et al.* (2017) ‘Final test results for the ground operations demonstration unit for liquid hydrogen’, *Cryogenics*, 88, pp. 147–155. Available at: https://doi.org/10.1016/j.cryogenics.2017.10.008.

Noussan, M. *et al.* (2020) ‘The Role of Green and Blue Hydrogen in the Energy Transition—A Technological and Geopolitical Perspective’, *Sustainability*, 13(1), p. 298. Available at: https://doi.org/10.3390/su13010298.

Obaidat, M. *et al.* (2018) ‘Energy and Exergy Analyses of Different Aluminum Reduction Technologies’, *Sustainability*, 10(4), p. 1216. Available at: https://doi.org/10.3390/su10041216.

Paulauskas, Vytautas, Paulauskas, D. and Paulauskas, Vytas (2023) ‘Impact of Port Clearance on Ships Safety, Energy Consumption and Emissions’, *Applied Sciences*, 13(9), p. 5582. Available at: https://doi.org/10.3390/app13095582.

Peace, C., Campbell, D. and Shen, W. (2023) ‘Green Hydrogen Export – Technical Readiness of Jetty-Less Marine Loading Terminals’, in *ADIPEC*. SPE. Available at: https://doi.org/10.2118/216910-MS.

Pekic, S. (2022) ‘Suiso Frontier brings world’s 1st LH2 shipment to Japan’. Available at: https://www.offshore-energy.biz/suiso-frontier-brings-worlds-1st-lh2-shipment-to-japan/.

Puig, M. and Darbra, R.M. (2019) ‘The Role of Ports in a Global Economy, Issues of Relevance and Environmental Initiatives’, in *World Seas: An Environmental Evaluation*. Elsevier, pp. 593–611. Available at: https://doi.org/10.1016/B978-0-12-805052-1.00034-6.

Raab, M., Maier, S. and Dietrich, R.-U. (2021) ‘Comparative techno-economic assessment of a large-scale hydrogen transport via liquid transport media’, *International Journal of Hydrogen Energy*, 46(21), pp. 11956–11968. Available at: https://doi.org/10.1016/j.ijhydene.2020.12.213.

Ratnakar, R.R. *et al.* (2021) ‘Hydrogen supply chain and challenges in large-scale LH2 storage and transportation’, *International Journal of Hydrogen Energy*, 46(47), pp. 24149–24168. Available at: https://doi.org/10.1016/j.ijhydene.2021.05.025.

‘Revised Basic Hydrogen Strategy Offers No Clear Path to Carbon Neutrality | Position Paper | Renewable Energy Institute’ (2022). Available at: https://www.renewable-ei.org/en/activities/reports/20230720.php.

Roos, T.H. (2021) ‘The cost of production and storage of renewable hydrogen in South Africa and transport to Japan and EU up to 2050 under different scenarios’, *International Journal of Hydrogen Energy*, 46(72), pp. 35814–35830. Available at: https://doi.org/10.1016/j.ijhydene.2021.08.193.

Saadi, F.H., Lewis, N.S. and McFarland, E.W. (2018) ‘Relative costs of transporting electrical and chemical energy’, *Energy & Environmental Science*, 11(3), pp. 469–475. Available at: https://doi.org/10.1039/C7EE01987D.

Saieva, G. (2013) *Port Management and Operations*. Informa Law from Routledge. Available at: https://doi.org/10.4324/9780203796689.

Semchukova, V. *et al.* (2024) *Hydrogen Infrastructure Analysis for the Port Applications [Slides]*. Golden, CO (United States). Available at: https://doi.org/10.2172/2459327.

Sharma, M. *et al.* (2024) ‘Green Hydrogen and Climatic Change: Current Status and Future Outlook’, in, pp. 31–54. Available at: https://doi.org/10.1021/bk-2024-1474.ch002.

Sonia Froufe, Charles–Henri Fredouet and Mame Gningue (2014) ‘Expertise modeling and transportation risk management: an application to container transportation security risk management’, *Journal of International Logistics and Trade*, 12(1), pp. 75–97. Available at: https://doi.org/10.24006/jilt.2014.12.1.004.

Spatolisano, E. *et al.* (2024) ‘Assessing opportunities and weaknesses of green hydrogen transport via LOHC through a detailed techno-economic analysis’, *International Journal of Hydrogen Energy*, 52, pp. 703–717. Available at: https://doi.org/10.1016/j.ijhydene.2023.08.040.

Superchi, F. *et al.* (2023) ‘Techno-economic analysis of wind-powered green hydrogen production to facilitate the decarbonization of hard-to-abate sectors: A case study on steelmaking’, *Applied Energy*, 342, p. 121198. Available at: https://doi.org/10.1016/j.apenergy.2023.121198.

Walsh, S.D.C. *et al.* (2021) 'Evaluating the economic fairways for hydrogen production in Australia', *International Journal of Hydrogen Energy*, 46(73), pp. 35985–35996. Available at: https://doi.org/10.1016/j.ijhydene.2021.08.142.

Wang, A. *et al.* (2020) 'European Hydrogen Backbone: HOW A DEDICATED HYDROGEN INFRASTRUCTURE CAN BE CREATED', *www.h2knowledgecentre.com* [Preprint]. Available at: https://www.h2knowledgecentre.com/content/researchpaper1676.

Wang, A. *et al.* (2021) 'Analysing Future Demand, Supply, and Transport of Hydrogen', *European Hydrogen Backbone* [Preprint], (June).

Xu, S. *et al.* (2024) 'Optimum investment strategy for hydrogen-based steelmaking project coupled with multiple uncertainties', *Journal of Environmental Management*, 356, p. 120484. Available at: https://doi.org/10.1016/j.jenvman.2024.120484.