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Review Article

A review on ports' readiness to facilitate international hydrogen trade

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HIGHLIGHTS

- Introducing ports' features in international hydrogen supply chains.
- Identifying possible early hydrogen exporting and importing ports.
- Identifying research gaps of ports' readiness for exporting and importing hydrogen.

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ABSTRACT

The existing literature on the hydrogen supply chains has knowledge gaps. Most studies focus on hydrogen production, storage, transport, and utilisation but neglect ports which are nexuses in the supply chains. To fill the gap, this paper focuses on ports' readiness for the upcoming hydrogen international trade. Potential hydrogen exporting and importing ports are screened. Ports' readiness for hydrogen export and import are reviewed from perspectives of infrastructure, risk management, public acceptance, regulations and standards, and education and training. The main findings are: (1) liquid hydrogen, ammonia, methanol, and LOHCs are suitable forms for hydrogen international trade; (2) twenty ports are identified that could be first movers; among them, twelve are exporting ports, and eight are importing ports; (3) ports' readiness for hydrogen international trade is still in its infancy, and the infrastructure construction or renovation, risk management measures, establishment of regulations and standards, education and training all require further efforts.

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Contents

Introduction

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 December 2022, 133 countries had set or proposed net-zero greenhouse gas (GHG) emissions targets. Most of 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 deep 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. The detail can be found in Table S1 in the supplementary material of this paper. 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 hydrogen 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 nexus in supply chains as they support interactions between global supply chains and regional production and consumption markets. Unfortunately, there is limited literature focused on ports in the H2 supply chains. Other energy sources, such as crude oil and liquified natural gas (LNG), have clear and mature technical pathways for bulk storage and handling and complete infrastructure in ports, while for the arrival of the H2 international trade, ports' readiness requires investigation. Against the background, this paper explores ports' readiness for exporting and importing H2 in terms of infrastructure, risk, public acceptance, regulation and standard development, and education and training. To achieve it, it is organised as follows. Methodology presents the methodology of this study. Ports' features in the international hydrogen supply chains, Possible early hydrogen exporting and importing ports and Ports' readiness for hydrogen trade critically reveal and analyse the port feature in international hydrogen supply chains, potential leading ports in exporting and importing H2, and the port readiness in terms of a few influential factors. Discussion describes the discussion before the conclusion in Concluding remarks.

Methodology

This study reviews academic and grey literature, including journal articles, government documents, government websites, medias, and industrial reports, to investigate ports' readiness for facilitating global H2 trade. Considering the rapid progress in the field of H2, it focuses on the most recent literature published in the past five years (2018–2022). Fig. 1 provides a flowchart of the literature review that consists of four phases and the objectives to achieve. Phase 1 reviews the H2 supply chain and identifies the critical links and their characteristics. Phase 2 identifies ports' features based on feasible H2 forms for international trade. Phase 3 identifies possible early H2 trade countries and ports. Phase 4 examines the ports' readiness.

Ports' features in the international hydrogen supply chains

This section discusses the review outcomes of phases 1 and 2. The international H2 supply chains are still under development; however, their characteristics could be envisaged based on status quo of the technologies. Ports' features in H2 Supply chains are outlined according to different technology pathways.

Hydrogen supply chains

The key functions and links in a typical H2 supply chain include production, conversion, storage, transport, distribution, re-conversion, and utilisation. 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 carbon dioxide (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 (CCS) 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 hydrogen and about 45 Mt mixed with other gases and used in industries in 2020 [6]. About 50% of annual pure hydrogen 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 [30]. 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 [31]. Ongoing innovation and scaling up are expected to bring green production process costs down and make it more competitive by 2025 or 2030 [32].

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 [33], liquefaction [34], and chemical compounding [35–37]. Currently, typical pressures of compressed hydrogen gas (CH2) are 35 MPa (the density is 23 kg/m^3) and 70 MPa (the density is 42 kg/m^3). H2 turns into a liquid when it is cooled to below -252.87 °C via a liquefaction process. Liquid hydrogen (LH2) has a density of 70.8 kg/m^3, 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 FCs only by evaporating. The promising chemical compounding forms are ammonia, methanol, or liquid organic hydrogen carriers (LOHCs) [38,39]. Ammonia is a compound of hydrogen and nitrogen in the form of NH3

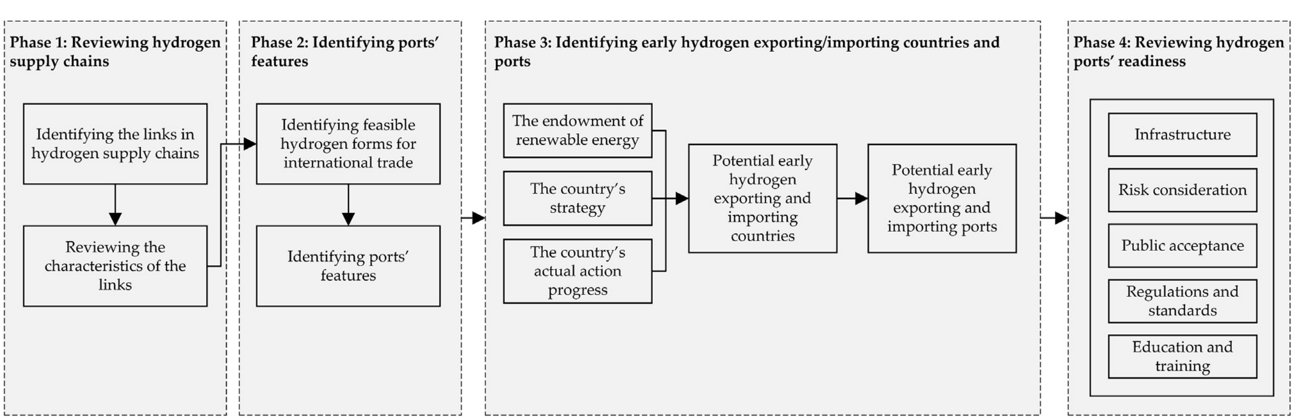

Fig. 1 – The flowchart of the review process and objectives.

synthesised via the Haber-Bosch process [40]. Methanol is a hydrogen carrier in the form of CH3OH. The reaction of H2 with CO2 to form methanol and water [41]. 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 [42]. 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 [43–45]. Methanol and LOHCs can be stored and transported in liquid forms at normal temperature and pressure [20,46].

H2, in any forms, 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 the 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 [47], internal combustion engines (ICE) [48], steam turbines (ST) [49], gas turbines (GT) [50], and burners [51].

Ports' infrastructure

As discussed above, the H2 forms could be CH2, LH2, ammonia, methanol and LOHCs. For international shipping, CH2 is not considered in this paper due to its low transport efficiency and lack of technological maturity for shipping, even though some conceptual CH2 ships have been designed [52], which might be suitable for some short routes, for example, less than 1000 km [53]. Therefore, LH2, ammonia, methanol, and LOHCs are the main focuses for international H2 trade.

LH2 has been used in the aerospace industry for decades [54], and micro supply chains have been formed in such countries as US, China, Japan, and Norway [55,56], laying the foundation for forming large-scale supply chains [57]. The world's first LH2 shipping from Australia to Japan was demonstrated in 2022 [58]. 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 [59–61], more LH2 ports might be developed. For such export, liquification facility is required within or near the port.

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 [62]. 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 [63].

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 [64,65]. Like ammonia, methanol is ready for immediate use as a feedstock in chemical processes and as a fuel [66–69].

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 [37,70,71]. The first small-scale transoceanic H2 shipping via MCH from Brunei to Japan was implemented in 2020 [72]. 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. 2 summarises the port infrastructure required under different H2 forms. 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 [73]. 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.

Possible early hydrogen exporting and importing ports

Identifying potential H2 energy exporters and importers is a prerequisite for identifying potential ports. Three factors determine the potential of an exporting or importing country: (1) The endowment of H2 production resources and the demand of H2; (2) The country's strategy; (3) The country's actual action progress.

The International Renewable Energy Agency (IRENA) identified the potential H2 exporters and importers [8]. As of September 2021, 41 import-export partnerships for low-carbon or carbon-neutral H2 have been established worldwide according to the literature [74]. Based on available information, this paper screens the potential early movers to identify the possible early H2 exporting and importing ports.

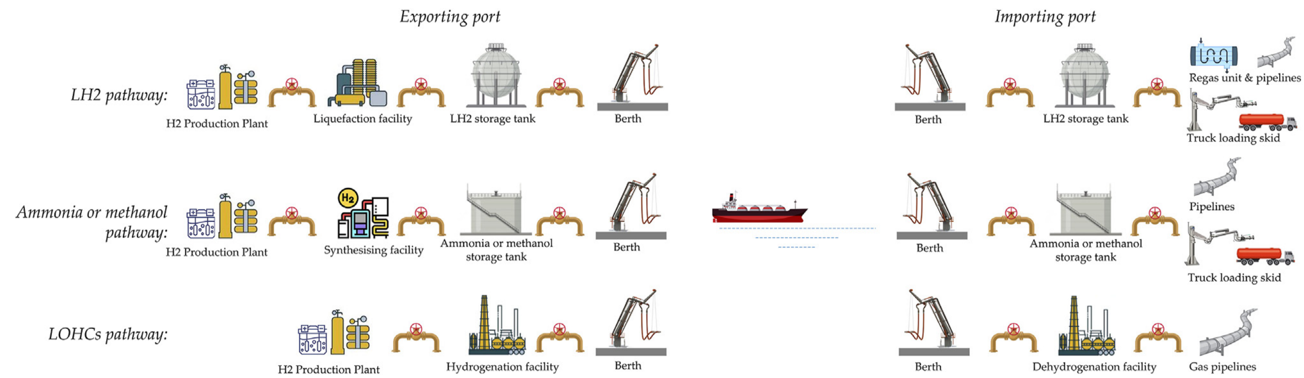

Fig. 2 – Hydrogen port infrastructure.

Potential early movers

This subsection identifies some countries that are expected to become the pioneers of the international hydrogen trade.

Potential early hydrogen exporting countries

According to the International Energy Agency (IEA), as of 2021, 989H2 production projects had been officially announced worldwide [75]. The capacities of these projects are synthesised in this paper, and the 38 countries with announced zero-carbon H2 production capacity greater than 1 ton/hour are shown in Fig. 3. The total announced capacity is 6900 tons/hour. Assuming 80% of the capacity is in operation, the annual production is equivalent to 48.35 Mt. The IEA projects that global annual H2 demand will be more than 200 Mt in 2030 and 530 Mt in 2050 [76,77]. 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 (48.35 Mt/year) meets about 24% of the demand in 2030 and about 9% in 2050. This data shows the positive progress of the production sector. Fig. 4 presents the top 20 countries and their capacities.

Based on the above three factors, this study identifies five possible early hydrogen exporters, including Australia, Chile, Mauritania, Saudi Arabia, and Norway.

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, see Table S1 in the supplementary material. These strategies involve Australia's bold vision of becoming a major H2 exporter [78]. 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 [79]. Seven hub regions have been identified and funded by the federal government, they are 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 [73]. Australia's policies and projects are ever growing, the information can be found on an online information-sharing portal HyResource [80]. 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

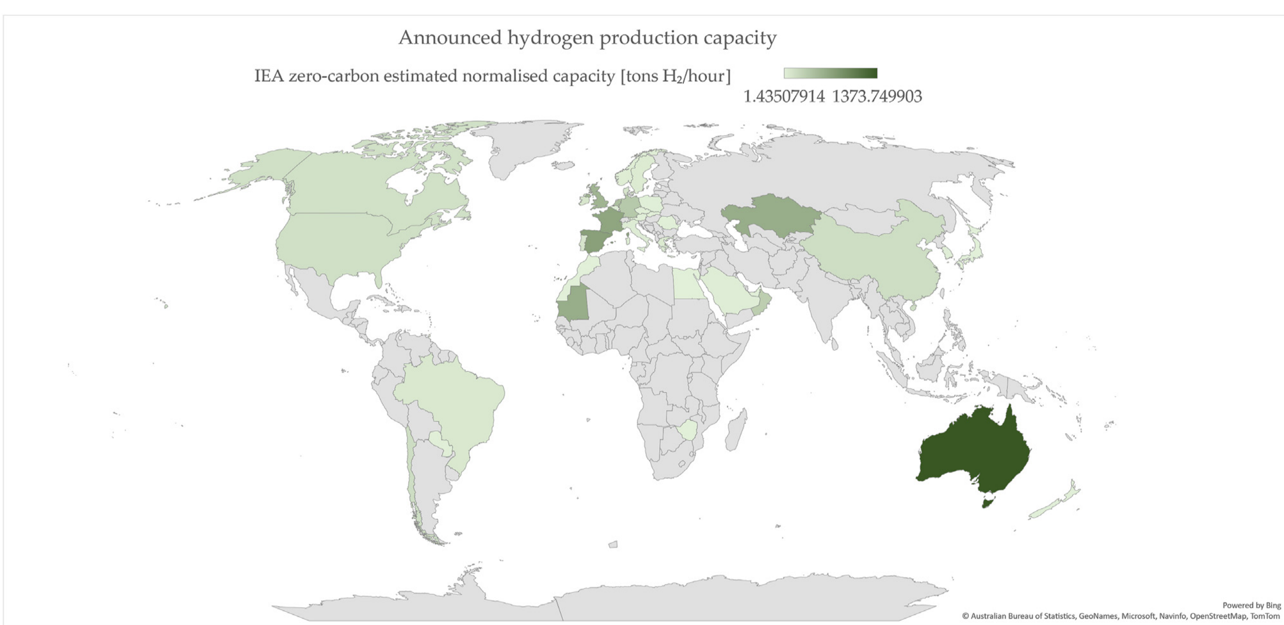

Fig. 3 – Announced zero-carbon estimated normalised hydrogen production capacity (data source from [75]).

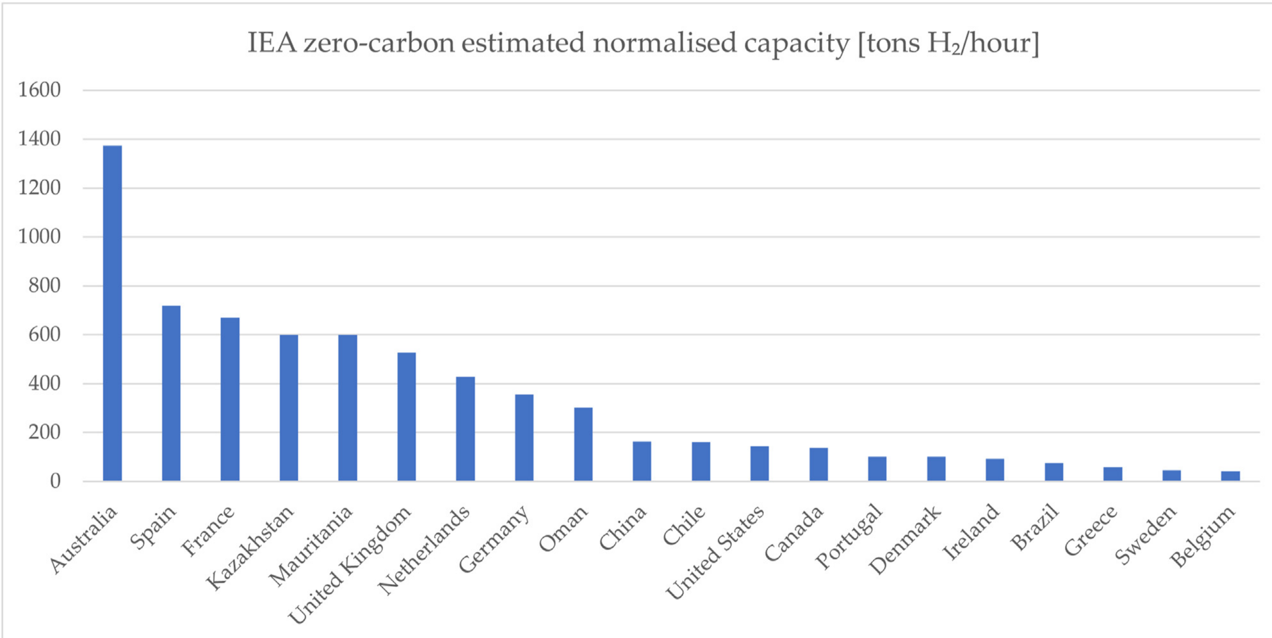

Fig. 4 – Top 20 countries by announced zero-carbon estimated normalised hydrogen production capacities (data source from [75]).

A$2.00–4.00/kg ($1.39–2.79/kg) in 2030 [81]. In practice, Australia has exported its first shipment of LH2 to the Port of Kobe in Japan from Victoria's Port of Hastings [58]. The port of Geelong in Victoria plans to spend A$100 million on a green H2 hub, including green ammonia capacity for export to Asia [82]. The Port of Bonython is being developed as a major hydrogen and ammonia export hub of the South Australia [83]. The Port of Newcastle has been funded to establish an initial 40 MW H2 production hub and consider the future around 1 GW capacity (0.15 Mt per year) for domestic and export use [84]. The Western Australia government plans to create five H2 hubs from Onslow to the Port of Hedland by 2030 [85]. The Port of Bell Bay in Tasmania plans to be a leading producer and exporter of green hydrogen [86], with 1000 MW green ammonia and 120 MW green methanol 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 [87]. The Port of Rotterdam has signed agreements with four Australian state governments to explore the possibility of importing hydrogen, including South Australia [88], Queensland [89], Western Australia [90], and Tasmania [91]. It is estimated that the demand for H2 exported from Australia will be at over 3 Mt per year by 2040 [32].

Chile has the resources of wind and solar to produce more than 1800 GW of renewable energy, which is 75 times the country's need for domestic consumption. In the country's National Green Hydrogen Strategy [92], the government set a goal to become the global leader in the production of green H2, to produce the cheapest green H2 with a price below $1.5/kgH2 by 2030, and to become a leading exporter by 2040. The Netherlands and Chile have been working together to create a H2 export corridor [93]. The Port of San Antonio has the potential to be a H2 exporting port [94].

Mauritania could be a H2 exporter with its rich solar and wind energy. The country aims to export green H2 after 2030 according to its national three-step H2 plan [95]. Mauritania has the potential to reduce the green production costs to $1.5/kg by 2030 or earlier becoming one of the cheapest hydrogen producers. A green hydrogen project in Mauritania with a capacity of up to 10 GW, known as “Project Nour”, has been announced [96]. The Port of Rotterdam signed an import agreement with the project [96]. The Port of Nouadhibou could be a H2 exporting port [97].

Saudi Arabia is a possible H2 exporter with its rich solar energy. According to the country's National Hydrogen Strategy [98], it aims to become the world's top hydrogen supplier. Saudi Arabia became the first to export blue ammonia to Japan in 2020 [99]. It is estimated that the green hydrogen production cost could fall to $1.48/kg by 2030 in the country, if renewable energy costs fall to $13/MWh. Then, the delivered cost from Saudi Arabia's western region to the Port of Rotterdam via the Suez Canal can be competitive [100]. A H2 production site in Yanbu, near the port, has been in operation since 2020 [101].

Norway is a potential H2 exporter. The Norwegian Government's hydrogen strategy stated that it is possible to export H2 to the rest of Europe [102]. Norway targets 30 GW offshore wind by 2040, and is intended to promote H2 exports [103]. The Port of Egersund has the potential to become an exporting port [104].

In summary, the reasons for above five countries being early H2 exporters are shown in Table 1.

Potential early hydrogen importing countries

By 2050, the total demand for H2 in the EU could rise from 10 Mt to 60 Mt. The EU will produce about half of the demand

Table 1 – Contributing factors to possible early hydrogen exporters.

	Factor (1): The endowment of H2 production resources and the demand of H2	Factor (2): strategy	Factor (3): actual progress
Australia	• Rich renewable energy resources • Potential production capacity exceeds demand	• Australia's National Hydrogen Strategy (To become one of the top three H2 exporters to Asian markets by 2030)	• Seven H2 hubs • Agreements with potential importers • Reducing H2 production costs • LH2 export demonstration
Chile	• Rich wind and solar resources • Potential production capacity exceeds demand	• National Green Hydrogen Strategy (To become a leading low-cost H2 exporter by 2040)	• Agreements with potential importers
Mauritania	• Rich wind and solar resource • Potential production capacity exceeds demand	• National Three-step H2 plan (To export green H2 after 2030)	• Green H2 production projects
Saudi Arabia	• Rich solar resource • Potential production capacity exceeds demand	• National Hydrogen Strategy (To become the world's top H2 supplier)	• H2 export pilot projects • Ammonia export demonstration
Norway	• Rich wind resource • Potential production capacity exceeds demand	• The Norwegian Government's hydrogen strategy (To export H2 to the rest of Europe)	• Green H2 production and export projects

by 2050, and the other half will be imported [105]. Some East Asian countries that are not rich in renewable energy sources have a high demand for importing H2. Based on the three factors, this subsection identifies the possible early importers including Germany, the UK, the Netherlands, Japan, South Korea, and Singapore.

Germany's National Hydrogen Strategy predicted the country's annual H2 demand will reach up to 2.7–3.6 Mt by 2030 [106]. Its domestic production meets less than 20% of the forecasted demand; hence more than 80% needs to be imported. The country has established import-export partnerships with many countries [107]. Germany expects to start importing green H2 from Australia in 2025 [108]. The port of Hamburg and the Port of Wilhelmshaven could be the H2 importing ports [109,110].

The Netherlands set the Government Strategy on Hydrogen in 2020 [111], stating the Port of Rotterdam will be the potential H2 hub. The port plans to start importing green H2 as early as 2025, supply 4.6 Mt/year of H2 into Europe by 2030 [112], and expects hitting 20 Mt/year by 2050 [113].

The UK issued the country's Hydrogen Strategy in 2021 [114]. It requires around 7.6–13.9 Mt of low-carbon H2 by 2050 [114]. The current H2 production capacity is 0.3–0.8 Mt, and only a fraction of them is low-carbon [115,116]. Therefore, in the short term, the UK could be a H2 importer to lower the risks of meeting expected demand. For example, the Port of Cromarty Firth will import green H2 from Norway [117]. However, in the long term, the government has ambitions to become an exporter, a report on its hydrogen export capability has been issued [118].

Japan issued its Basic Hydrogen Strategy in 2017 [119], stating H2 import infrastructure would be developed. Its H2 demand will reach up to 3.0 Mt/year by 2030 and 20 Mt/year by 2050, mainly from overseas [119,120]. Japan has established supply chains cooperation with Australia, Brunei, and Saudi Arabia [107,121]. Importing H2 in the form of LH2, LOHCs, and ammonia is expected in Japan [122]. 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 [58,72,99]. Japan's Kobe port and Onahama port are exploring their future H2 and ammonia import potential [123,124].

South Korea aims to expand its annual H2 consumption to 5.26 Mt by 2040 according to the Hydrogen Economy Roadmap of Korea [125], and most of the demand will be met by import. Another prediction shows the country's H2 demand will reach up to 3.9 Mt/year by 2030 and 27.9 Mt/year by 2050, and 1.96 Mt/year of green H2 will be imported from overseas [126]. In 2021, an energy company signed an agreement with the Port of Townsville of Australia to import H2 to South Korea in the next decade [127]. In the same year, the government announced that the country would import ammonia from Australia, Russia, and the Middle East [128]. In 2022, Australia and South Korea announced they would invest up to $100 million towards initiatives under a Low and Zero Emissions Technology Partnership [129]. The Port of Ulsan has the potential to become a H2 importing port [130].

Singapore issued its National Hydrogen Strategy in 2022 [131], predicting H2 could supply up to half of the country's power needs by 2050, thus requiring the development of import and storage facilities, and distribution networks. Besides domestic use, H2 and its derivatives are potential alternatives to fossil fuels in the maritime sector. Singapore is the world's largest bunker port. In 2021, its total bunker sales amounted to about 50 Mt [132], which accounted for about one-sixth of the global consumption. As the shipping industry transitions to zero-carbon fuels, Singapore strongly demands H2-based fuels. It is predicted that ammonia and methanol would represent 35% and 14% of the maritime fuel mix respectively in 2050 [133]. In 2021, Australia and Singapore announced that they would establish a $30 million partnership to accelerate the deployment of low emissions fuels and technologies to reduce emissions in maritime and port operations [134]. In 2022, Singapore's sovereign wealth fund, GIC, became a strategic investor in two proposed green H2 projects in Western Australia [135].

Table 2 – Contributing factors to possible early hydrogen importers.

	Factor (1): The endowment of H2 production resources and the demand of H2	Factor (2): strategy	Factor (3): actual progress
Germany	• Annual H2 demand will be 2.7–3.6 Mt by 2030 • Domestic H2 production is limited	• The National Hydrogen Strategy (To pave the way for H2 imports)	• Import-export partnerships with 13 countries
The Netherlands	• Annual H2 import will be 4.0 Mt by 2030 • Domestic H2 production cannot meet the demand in short term	• Government Strategy on Hydrogen (To act as a H2 hub)	• Agreements with potential H2 exporters
The UK	• Annual H2 demand will be 7.6–13.0 Mt in 2050 • Domestic H2 production cannot meet the demand in short term	• UK Hydrogen Strategy (Import/ export infrastructure in place from mid-2030s)	• Ports actions
Japan	• Annual H2 demand will be 3.0 Mt by 2030 and 20 Mt by 2050 • Domestic H2 production is limited	• Basic Hydrogen Strategy (To develop H2 import infrastructure)	• LH2, ammonia, and LOHCs import pilot projects
South Korea	• Annual H2 demand will be 3.9 Mt by 2030 and 27.9 Mt by 2050 • Domestic H2 production is limited	• Hydrogen Economy Roadmap of Korea (To develop H2 import infrastructure)	• Agreements with potential H2 exporters
Singapore	• H2 could supply up to 50% of the country's power demand by 2050 • H2-based bunker fuel demand is huge • Domestic H2 production is limited	• Singapore's National Hydrogen Strategy (To develop H2 import infrastructure)	• Agreements with potential H2 exporters • Investments in potential H2 exporters

In summary, the reasons for the above six countries being early H2 importers are shown in Table 2.

Potential early hydrogen ports

Based on the above analysis, Fig. 5 presents 20 possible early hydrogen ports. Twelve ports are exporting ports including the Ports of Hedland, Darwin, Townsville, Newcastle, Hastings, Geelong, Bonython and Bell Bay in Australia, the Port of San Antonio in Chile, the Port of Nouadhibou in Mauritania, the Port of Yanbu in Saudi Arabia, and the Port of Egersund in Norway; and eight ports are importing ports including the Port of Hamburg and the Port of Wilhelmshaven in Germany, the Port of Rotterdam in the Netherlands, the port of Cromarty Firth in the UK, the ports of Kobe and Onahama in Japan, the Port of Ulsan in South Korea, and the Port of Singapore.

The involvement of shipping companies is essential to realise the H2 transoceanic trade in practice. Pioneering

Fig. 5 – Possible early hydrogen ports (the green mark represents the exporting port; the blue mark represents the importing port). (For interpretation of the references to color/colour in this figure legend, the reader is referred to the Web version of this article.)

shipping companies that have been studying or demonstrating the H2 shipping include Mitsui OSK Lines [136], NYK Line [137], and Shell Japan [138].

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.

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 [139]. Only large-scale LH2 storage tanks and loading/unloading equipment are still in their infancy [140]. In the world's first LH2 international trade pilot project, the capacity of LH2 tanks in the Port of Kobe is 2500 m^3. At present, there is no existing reference design for large-scale LH2 storage tanks [141]. 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 [140,141]. 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 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. The port of Rotterdam issued its position paper on various H2 forms [142]. Green ammonia terminal construction is on the way in the port of Rotterdam [143]. In Australia, in addition to the Port of Hastings, the Port of Townsville is also planning an LH2 exporting project [144]. Green ammonia plants have been planned in the Port of Hedland [85], Bonython [83], Bell Bay [145], and Townsville [144]. Green methanol projects are considered by the Port of Bell Bay [146]. 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 [124]. The status of these infrastructure has been benchmarked, which is a basic step towards identifying the technology improvements needed for infrastructure to support the global H2 supply chains. H2 can be also seen as an opportunity for existing oil and gas infrastructure operators. For instance, some energy companies plan to make the LNG importing terminals hydrogen-ready or ammonia-ready [147,148].

Risk consideration

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

Liquid hydrogen

H2 faces increased public concern about risks due to major accidents, including the Hindenburg disaster in 1937 [149], the Challenger disaster in 1981 [149], and the tank explosion in South Korea in 2019 [150]. 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 the comparison of the risk-related properties of LH2 and LNG [151,152].

Accordingly, some main hazards can be summarised as follows [57,149,153].

(1) 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.

Table 3 – Comparison of the properties of LH2 and LNG [151,152].

	LH2	LNG
Boiling point (K)[a]	20.3	111.6
Liquid density (kg/m^3)[a]	70.8	422.5
Gas density (kg/m^3)[b] (Air: 1.198)	0.084	0.668
Latent heat of vaporization (J/g)[a]	448.7	510.4
Lower flammable limit (% volume percentage)[c]	4.0	5.3
Upper flammable limit (% volume percentage)[c]	75.0	17.0
Lower detonation limit (% volume percentage)[c]	18.3	6.3
Upper detonation limit (% volume percentage)[c]	59.0	13.5
Minimum ignition energy (mJ)[c]	0.017	0.274
Auto-ignition temperature (°C)[c]	585	537
Diffusivity in air (cm^2/s)	0.61	0.16
Critical temperature (K)	33.19	190.55
Critical pressure (kPa)	1315	4595
Viscosity (10^{-6} g/cm.s)[b]	13.49	116.79
Flame temperature in air (°C)	2396	2230
Maximum burning speed (m/s)	2.6	0.43

Note:
[a] At 101.325 kPa.
[b] At 20 °C and 101.325 kPa.
[c] Air mixture at 25 °C and 101.3 kPa.

(2) 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 [154].

(3) 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 be put out. It has a high probability of explosion in an enclosed space.

(4) Cryogenic

LH2 tanks, piping systems, and equipment need 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 [155].

(5) Rapid evaporation

The boiling point and latent heat of vaporization of hydrogen are low, leading to the high evaporation rate. If LH2 is completely vaporised 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 the risk identification and control. For example, US NASA reviewed LH2 incidents in 1974 [156], and concluded that the number of accidents could have been reduced if the established NASA rules and regulations had been followed. Lowesmith et al. [157] reviewed LH2 incidents associated with liquefaction, storage, and transport. The result showed 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. According to the safety reports on the 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. No single subsystem dominated events [158]. The existing knowledge about LH2 safety is asset for ports to get ready for LH2 handling.

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 [159]. 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 [40]. 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 [160]. Furthermore, ammonia has a serious impact on marine life when spilling into the ocean [43,161,162].

Quest [163] 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 [164] 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 et al. [165] 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.

Methanol

Methanol is toxic to humans through ingestion, inhalation of vapours or skin absorption. If a person ingests 10 ml 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 [166]. 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 [167]. 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 [168]. Therefore, material selection for equipment needs to follow regulations and standards [169]. Methanol has been handled in ports for many years, and experience have been amassed in risk management of the methanol handling.

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 [39]; however, fire and explosion risks of MCH deserve attention. LOHCs are like oils whose risk managements are well-established in ports.

The comparison of the physical, chemical and risk properties of different H2 forms can be found in Table S2 in the supplementary material of this paper.

Public acceptance

It is necessary to consider public acceptance when implementing H2 technologies on a large scale. Some scholars have conducted hydrogen public acceptance studies. For example, within a large-scale H2 infrastructure project, quantitative data on the acceptance was gathered among the German population [170]. The results confirm the positive perception of hydrogen 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 hydrogen, hydrogen infrastructure and fuel cell vehicle [171]. The study found that people have become a little more positive about hydrogen 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 [172]. 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 [173]. 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 for 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.

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 clear; however, regulatory uncertainty and the lack of standards are major barriers in implementing 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.

Port regulations and standards focus on project planning, environmental assessment, safety assessment, infrastructure construction, and cargo handling. Based on the identified early H2 ports, this study focuses on regulations and standards in Australia, Chile, Saudi Arabia, Norway, EU countries, the UK, Japan, South Korea, and Singapore. There is no literature about Mauritania's regulation and standard progress.

(1) Australia

Specialised H2 infrastructure in Australia requires local, state or territory, and federal level planning and environmental approvals. Generally, existing planning approval regimes will 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 [174]. 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 [175]. In terms of standards, Standards Australia adopted eight key international H2 standards in 2020 [176], 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 [175]. However, tailor-made regulations and standards for ports are still gaps.

(2) Chile

Chile has yet to establish regulations for H2. However, advances were made in 2020 that sufficient powers were granted to the Ministry of Energy to regulate the H2 industry. Despite recent legal undertakings and proposals, the currently existing regulatory framework of H2 is still insufficient for all of its handlings including ports [177].

(3) Saudi Arabia

There is no dedicated legislation for H2 projects in Saudi Arabia. The Ministry of Energy, Industry and Mineral Resources which regulates, develops, and implements policies relating to oil and gas will develop regulations for hydrogen ports [178].

(4) Norway

Norway does not have a well-defined legal and regulatory framework for H2 projects [179]. However, H2 handling in Norway is regulated in the Regulations on the Handling of Dangerous Substances [179]. It stipulates that a risk assessment for H2 plants must be prepared. To achieve sufficient safety for third parties, it is important that the H2 handling takes place at a sufficient distance from surrounding objects. The regulation requires companies to document whether there is a need for spatial measures restrictions on H2 handling facilities. This is important to be considered when H2 ports are being established.

(5) EU countries

The EU is actively promoting the establishment of H2 regulations. In 2018, the EU Parliament called on the Commission to revise the 2014 Alternative Fuels Infrastructure Directive (AFID) to fill the gaps in the build-up of H2 infrastructure [180]. In 2021, the European Commission adopted a legislative proposal to recast the 2009 EU Gas Directive, as part of the proposed H2 and decarbonised gas markets package [180]. In the same year, the Commission proposed to repeal the AFID and replace it with a regulation, suggesting that the change of instrument is needed to ensure “swift and coherent development” of the H2 infrastructure network across the EU [181]. The Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) regulates the road transport of H2 in the EU countries [182].

In terms of technical standards, most EU countries' standards have been harmonised with international (ISO, IEC) or European (EN) standards. New standards are essentially developed only within the framework of ISO, IEC, CEN, or CENELEC [183]. In the existing standard system, the standards applicable to ammonia, methanol and LOHCs are relatively complete, but the standards applicable to LH2 are insufficient. Although there are some standards applicable to cryogenic liquids, most of these standards are based on LNG. These standards should be revised to include risk control measures for LH2.

(6) The UK

In the UK, hydrogen 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 [184]. The UK adopted ADR regulating the road transport of H2 [184].

(7) Japan

H2 is regulated as a type of high-pressure gas in Japan. The High-Pressure Gas Safety Act plays a central role [122]. 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 standardization [140]. 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 hydrogen has been issued.

(8) South Korea

The South Korean's Hydrogen Safety Management Act came into force on February 5, 2021 [185]. The Act describes the safety regulations that a manufacturer of H2-related components must comply with, governs the handling, import and export of H2 related components, such as fuel cells and extractors. However, port infrastructure is not mentioned in the Act.

(9) Singapore

Singapore does not have a specific or well-defined H2 legislative framework. H2 is regulated as a flammable material under the Fire Safety Act and its subsidiary Fire Safety Regulations. H2 importers need to be cognisant of the provisions in the Maritime and Port Authority of Singapore Act and its subsidiary Dangerous Goods, Petroleum and Explosives Regulations 2005. In 2021, an alliance was announced with an aim to accelerate the adoption of H2 as an energy source in Singapore. The parties intend to work together on developing safety requirements for H2 as a fuel source, infrastructure requirements for H2 storage and local transportation, and offshore H2 technology applications [186].

Overall, it is concluded that the lack of regulations and standards for ports is still a barrier to realise the international H2 trade. In this regard, international organisations are expected to formulate unified H2 port standards to promote the formation of the supply chains.

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 [187]. Japan has established a personnel training centre for H2. The UK's Health and Safety Executive provides H2 safety training service [188]. However, these training services have yet to cover H2 handlings in ports in a comprehensive manner.

Discussion

From the analysis in this paper, ports are preparing to facilitate the formation of H2 international supply chains, however, there are still gaps to be filled in terms of infrastructure construction, risk management, regulations and standards, and education and training. To ensure the healthy development of H2 ports, this section briefly undertakes the relevant discussion from four aspects.

Demonstrating the feasibility of H2 ports through pilot projects

Safety and reliability of H2 and its derivatives must be successfully proven in the pilot projects before the technologies can be fully adopted. The existing LH2 shipping pilot project from the Port of Hastings to the Port of Kobe is a pioneer, even the capacity is small. More pilot projects are needed. Tangible case studies can increase awareness and support long-term planning and buildout of infrastructure.

Comparing the history of LNG trade, the large-scale H2 shipping can be expected. The development of the LNG shipping is originated from a pilot project. World's first LNG ship

"Methane pioneer" delivered the first-ever transoceanic cargo of LNG in 1959, the capacity of the ship was just 5123 m^3 [189]. After ten years, in 1969, the LNG carrier capacity increased to 70,000 m^3. In the 1980s, LNG ships trended towards a 125,000 m^3 standard. Later, economies of scale and new technologies gave rise to increased ship sizes of 160,000 to 180,000 m^3, with the newest generation of ships being 216,000 to 266,000 m^3 [190].

Providing government-level supports

H2 trade is still in its infancy and many aspects remain unknown. Government funding is indispensable. For example, large-scale port infrastructure development funding is needed; the funding is also needed to accelerate the development of risk management methods, regulations and standards, education and training courses. Leaving the development of the H2 energy industry entirely in the hands of the free market may delay the goal of decarbonisation.

Decarbonising ports through hydrogen while preparing export and import

While the port is preparing for importing or exporting H2, it will inevitably usher in the decarbonisation of itself and its surroundings. H2 is not only a commodity circulating through ports, but also brings opportunities for the decarbonisation of ports. Vehicles, service ships, port machineries, and shore power facilities in ports can be converted to accommodate H2. Some ports have taken actions, such as the Port of Qingdao in China [191], the Port of Yokohama in Japan [192], the Port of Auckland in New Zealand [193], the Port of Antwerp in Belgium [194], the Port of Rotterdam in the Netherlands [195], the Port of Valencia in Spain [196], and the Port of Los Angeles in US [197]. Large GHG emitters such as cement, steel production bases, and petrochemical industry bases around ports can also use ports' H2 infrastructure to realise the transformation of H2-based energy and raw materials. The shipping industry is making a big move towards using H2-based alternative fuels, and the H2 transformation of bunkering services in ports will be a prerequisite for this transition.

Paying enough attention to hydrogen's drawbacks

Nothing is perfect. The GHG effect of H2 itself is often overlooked. H2 reacts with hydroxyl radicals in the troposphere, releasing H2 into the atmosphere disrupts the distribution of methane and ozone, the second and third largest GHGs after CO2. Therefore, H2 is an indirect GHG with a global warming potential (GWP) of 5.8 over a 100-year time horizon [198]. Careful attention must be paid to minimising H2 leakage in ports. A large amount of CO2 is emitted when manufacturing renewable energy infrastructure such as wind turbines and solar panels and building port storage infrastructure and ships [199]. Therefore, it is suggested to use life cycle GHG emission assessment to demonstrate and certificate the cleanness of H2.

Concluding remarks

This work focuses on the ports' readiness for the upcoming international H2 trade. The main findings are:

- LH2 and hydrogen carriers including ammonia, methanol, and LOHCs are suitable for H2 international trade through ports.
- Twenty possible early hydrogen ports are identified, including twelve exporting and eight importing ports.
- The port's readiness for the H2 international trade is still in its infancy. Infrastructure construction or renovation, risk management measures, establishment of regulations and standards, education and training all require more efforts. The upstream, midstream, and downstream related enterprises in the H2 energy industry and the government need to form a joint force to accelerate the formation of the international H2 supply chains.

The identified gaps suggest the following specific directions for future work.

- 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 standardization perspective.
- Effective information and knowledge-sharing platforms need to be established to promote public acceptance of H2 ports.
- Harmonised international regulations and standards for ports' H2 handling are expected to be developed.
- Education and training courses are required for H2 handlings in ports.

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Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2023.01.220.

Abbreviations

ADR	The European Agreement concerning the International Carriage of Dangerous Goods by Road
AFID	Alternative Fuels Infrastructure Directive
CCS	Carbon capture and storage
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CH2	Compressed hydrogen gas
CH3OH	Methanol
CO2	Carbon dioxide
DBT	Dibenzyl toluene
EN	European Norm
EU	European Union
FC	Fuel cells
GHG	Greenhouse gas
GT	Gas turbines
GWP	Global warming potential
H2	Hydrogen
HSE	The Health and Safety Executive
ICE	Internal combustion engines
IDLH	Immediately dangerous to life or health
IEC	International Electrotechnical Commission
IEA	International Energy Agency
ISO	International Organization for Standardization
IRENA	International Renewable Energy Agency
LH2	Liquid hydrogen
LNG	Liquified natural gas
LOHC	Liquid organic hydrogen carrier
LPG	Liquefied petroleum gas
MCH	Methylcyclohexane
Mt	Million tons
NASA	The National Aeronautics and Space Administration
NDC	Nationally Determined Contributions
NH3	Ammonia
NIMBY	Not In My Back Yard
PPM	Parts per million
ST	Steam turbines
UK	The United Kingdom of Great Britain and Northern Ireland
US	United States of America

REFERENCES

[1] Net Zero Tracker. Global net zero covergage. 2022.

[2] Whetton, A.K.T.D.M.D.Y.S. Advancing Hydrogen: learning from 19 plans to advance hydrogen from across the globe. 2019.

[3] Por, Y.-L. Great Expectations: Asia, Australia and Europe Leading. Emerging green hydrogen economy, but project delays likely. 2020.

[4] WPR. CO2 emissions by country. 2022. Available online, https://worldpopulationreview.com/country-rankings/co2-emissions-by-country. [Accessed 30 June 2022].

[5] Hydrogen Council. Hydrogen scaling up: a sustainable pathway for the global energy transition. Brussels: Belgium; 2017.

[6] WNA. Hydrogen Production and Uses. Available online, https://www.world-nuclear.org/information-library/energy-and-the-environment/hydrogen-production-and-uses.aspx. [Accessed 20 June 2022].

[7] IRENA. World energy transitions outlook: 1.5°C pathway. Abu Dhabi: International Renewable Energy Agency; 2022.

[8] IRENA. Geopolitics of the energy transformation : the hydrogen factor. 2022. Abu Dhabi.

[9] Pflugmann F, Blasio ND. Geopolitical and Market Implications of Renewable Hydrogen. Harvard Kennedy School: Cambridge, the UK; 2020. p. 23–5.

[10] Ochoa Robles J, De-León Almaraz S, Azzaro-Pantel C. Chapter 2-hydrogen supply chain design: key technological components and sustainable assessment. In: Azzaro-Pantel C, editor. Hydrogen supply chains. Academic Press; 2018. p. 37–79.

[11] Acar C, Dincer I. Selection criteria and ranking for sustainable hydrogen production options. Int J Hydrogen Energy 2022;47:40118–37. https://doi.org/10.1016/j.ijhydene.2022.07.137.

[12] Aydin MI, Dincer I. A life cycle impact analysis of various hydrogen production methods for public transportation sector. Int J Hydrogen Energy 2022;47:39666–77. https://doi.org/10.1016/j.ijhydene.2022.09.125.

[13] Stenina I, Yaroslavtsev A. Modern technologies of hydrogen production. Processes 2023;11:56. https://doi.org/10.3390/pr11010056.

[14] Moritz M, Schönfisch M, Schulte S. Estimating global production and supply costs for green hydrogen and hydrogen-based green energy commodities. Int J Hydrogen Energy 2022. https://doi.org/10.1016/j.ijhydene.2022.12.046.

[15] Panić I, Cuculić A, Ćelić J. Color-coded hydrogen: production and storage in maritime sector. J Mar Sci Eng 2022;10:1995. https://doi.org/10.3390/jmse10121995.

[16] Faye O, Szpunar J, Eduok U. A critical review on the current technologies for the generation, storage, and transportation of hydrogen. Int J Hydrogen Energy 2022;47:13771–802. https://doi.org/10.1016/j.ijhydene.2022.02.112.

[17] Wijayanta AT, Oda T, Purnomo CW, Kashiwagi T, Aziz M. Liquid hydrogen, methylcyclohexane, and ammonia as potential hydrogen storage: comparison review. Int J Hydrogen Energy 2019;44:15026–44. https://doi.org/10.1016/j.ijhydene.2019.04.112.

[18] Amirthan T, Perera MSA. The role of storage systems in hydrogen economy: a review. J Nat Gas Sci Eng 2022;108:104843. https://doi.org/10.1016/j.jngse.2022.104843.

[19] Kim C, Cho SH, Cho SM, Na Y, Kim S, Kim DK. Review of hydrogen infrastructure: the current status and roll-out strategy. Int J Hydrogen Energy 2023;48:1701–16. https://doi.org/10.1016/j.ijhydene.2022.10.053.

[20] Raab M, Maier S, Dietrich R-U. Comparative techno-economic assessment of a large-scale hydrogen transport via liquid transport media. Int J Hydrogen Energy 2021;46:11956–68. https://doi.org/10.1016/j.ijhydene.2020.12.213.

[21] Johnston C, Ali Khan MH, Amal R, Daiyan R, MacGill I. Shipping the sunshine: an open-source model for costing renewable hydrogen transport from Australia. Int J Hydrogen Energy 2022;47:20362–77. https://doi.org/10.1016/j.ijhydene.2022.04.156.

[22] Okunlola A, Giwa T, Di Lullo G, Davis M, Gemechu E, Kumar A. Techno-economic assessment of low-carbon hydrogen export from western Canada to eastern Canada, the USA, the asia-pacific, and Europe. Int J Hydrogen Energy 2022;47:6453–77. https://doi.org/10.1016/j.ijhydene.2021.12.025.

[23] Burdack A, Duarte-Herrera L, López-Jiménez G, Polklas T, Vasco-Echeverri O. Techno-economic calculation of green

hydrogen production and export from Colombia. Int J Hydrogen Energy 2023;48:1685–700. https://doi.org/10.1016/j.ijhydene.2022.10.064.

[24] Borsboom-Hanson T, Patlolla SR, Herrera OE, Mérida W. Point-to-point transportation: the economics of hydrogen export. Int J Hydrogen Energy 2022;47:31541–50. https://doi.org/10.1016/j.ijhydene.2022.07.093.

[25] Camacho MdlN, Jurburg D, Tanco M. Hydrogen fuel cell heavy-duty trucks: review of main research topics. Int J Hydrogen Energy 2022;47:29505–25. https://doi.org/10.1016/j.ijhydene.2022.06.271.

[26] Sun Z, Hong J, Zhang T, Sun B, Yang B, Lu L, Li L, Wu K. Hydrogen engine operation strategies: recent progress, industrialization challenges, and perspectives. Int J Hydrogen Energy 2023;48:366–92. https://doi.org/10.1016/j.ijhydene.2022.09.256.

[27] Öberg S, Odenberger M, Johnsson F. The value of flexible fuel mixing in hydrogen-fueled gas turbines – a techno-economic study. Int J Hydrogen Energy 2022;47:31684–702. https://doi.org/10.1016/j.ijhydene.2022.07.075.

[28] Teoh YH, How HG, Le TD, Nguyen HT, Loo DL, Rashid T, Sher F. A review on production and implementation of hydrogen as a green fuel in internal combustion engines. Fuel 2023;333:126525. https://doi.org/10.1016/j.fuel.2022.126525.

[29] Di Ilio G, Di Giorgio P, Tribioli L, Bella G, Jannelli E. Preliminary design of a fuel cell/battery hybrid powertrain for a heavy-duty yard truck for port logistics. Energy Convers Manag 2021;243:114423. https://doi.org/10.1016/j.enconman.2021.114423.

[30] Van Hoecke L, Laffineur L, Campe R, Perreault P, Verbruggen SW, Lenaerts S. Challenges in the use of hydrogen for maritime applications. Energy Environ Sci 2021;14:815–43. https://doi.org/10.1039/D0EE01545H.

[31] DW. The truth about hydrogen. 2022. https://www.youtube.com/watch?v=AGTjKJHu99c&t=15s.

[32] ANZ. The ANZ hydrogen handbook-AH2. 2022.

[33] Elberry AM, Thakur J, Santasalo-Aarnio A, Larmi M. Large-scale compressed hydrogen storage as part of renewable electricity storage systems. Int J Hydrogen Energy 2021;46:15671–90. https://doi.org/10.1016/j.ijhydene.2021.02.080.

[34] Zhu J, Wang G, Li Y, Duo Z, Sun C. Optimization of hydrogen liquefaction process based on parallel genetic algorithm. Int J Hydrogen Energy 2022;47:27038–48. https://doi.org/10.1016/j.ijhydene.2022.06.062.

[35] Paul A, Martins LMDRS, Karmakar A, Kuznetsov ML, Novikov AS, Guedes da Silva MFC, Pombeiro AJL. Environmentally benign benzyl alcohol oxidation and C-C coupling catalysed by amide functionalized 3D Co(II) and Zn(II) metal organic frameworks. J Catal 2020;385:324–37. https://doi.org/10.1016/j.jcat.2020.03.035.

[36] Novikov AS, Kuznetsov ML, Rocha BGM, Pombeiro AJL, Shul'pin GB. Oxidation of olefins with H2O2 catalysed by salts of group III metals (Ga, In, Sc, Y and La): epoxidation versus hydroperoxidation. Catal Sci Technol 2016;6:1343–56. http://10.1039/C5CY01367D.

[37] Sekine Y, Higo T. Recent trends on the dehydrogenation catalysis of liquid organic hydrogen carrier (LOHC): a review. Top Catal 2021;64:470–80. https://10.1007/s11244-021-01452-x.

[38] Hydrogen Council. Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness. 2021. p. 20–3.

[39] Meca VL, d'Amore-Domenech R, Crucelaegui A, Leo TJ. Large-scale maritime transport of hydrogen: economic comparison of liquid hydrogen and methanol. ACS Sustainable Chem Eng 2022;10:4300–11. https://10.1021/acssuschemeng.2c00694.

[40] MacFarlane DR, Cherepanov PV, Choi J, Suryanto BHR, Hodgetts RY, Bakker JM. Ferrero vallana, F.M.; simonov, A.N. A roadmap to the ammonia economy. Joule 2020;4:1186–205. https://doi.org/10.1016/j.joule.2020.04.004.

[41] IRENA. Innovation outlook renewable methanol. Abu Dhabi: International Renewable Energy Agency; 2021.

[42] Niermann M, Timmerberg S, Drünert S, Kaltschmitt M. Liquid Organic Hydrogen Carriers and alternatives for international transport of renewable hydrogen. Renew Sustain Energy Rev 2021;135:110171. https://doi.org/10.1016/j.rser.2020.110171.

[43] Valera-Medina A, Amer-Hatem F, Azad AK, Dedoussi IC, de Joannon M, Fernandes RX, et al. Review on ammonia as a potential fuel: from synthesis to economics. Energy Fuels 2021;35(9):6964–7029. https://doi.org/10.1021/acs.energyfuels.0c03685.

[44] Al-Aboosi FY, El-Halwagi MM, Moore M, Nielsen RB. Renewable ammonia as an alternative fuel for the shipping industry. Curr Opin Chem Eng 2021;31:100670. https://doi.org/10.1016/j.coche.2021.100670.

[45] Fan H, Enshaei H, Jayasinghe SG, Tan SH, Zhang C. Quantitative risk assessment for ammonia ship-to-ship bunkering based on Bayesian network. Process Saf Prog 2022;41:395–410. https://doi.org/10.1002/prs.12326.

[46] McKinlay CJ, Turnock SR, Hudson DA. Route to zero emission shipping: hydrogen, ammonia or methanol? Int J Hydrogen Energy 2021;46:28282–97. https://doi.org/10.1016/j.ijhydene.2021.06.066.

[47] Wang Y, Pang Y, Xu H, Martinez A, Chen KSPEM. Fuel cell and electrolysis cell technologies and hydrogen infrastructure development – a review. Energy Environ Sci 2022;15:2288–328. https://10.1039/D2EE00790H.

[48] Bao L-z, Sun B-g, Luo Q-h, Li J-c, Qian D-c, Ma H-y, Guo Y-j. Development of a turbocharged direct-injection hydrogen engine to achieve clean, efficient, and high-power performance. Fuel 2022;324:124713. https://doi.org/10.1016/j.fuel.2022.124713.

[49] Weiliang W, Shusheng Z, Ce Z. Study of the hydrogen-steam turbine composite cycle. Procedia CIRP 2015;26:735–9. https://doi.org/10.1016/j.procir.2015.01.014.

[50] Ugarte OJ, Menon S, Rattigan W, Winstanley P, Saxena P, Akiki M, Tarver T. Prediction of pressure rise in a gas turbine exhaust duct under flameout scenarios while operating on hydrogen and natural gas blends. J Eng Gas Turbines Power 2022;144. https://10.1115/1.4052358.

[51] Zhao Y, Hickey B, Srivastava S, Smirnov V, McDonell V. Decarbonized combustion performance of a radiant mesh burner operating on pipeline natural gas mixed with hydrogen. Int J Hydrogen Energy 2022;47:18551–65. https://doi.org/10.1016/j.ijhydene.2022.04.003.

[52] Peacock B. Compressed green hydrogen ship for Aussie exports deemed 'highly competitive'. Available online, https://www.pv-magazine-australia.com/2021/03/02/compressed-green-hydrogen-ship-for-aussie-exports-deemed-highly-competitive/. [Accessed 3 June 2022].

[53] Babarit A, Gilloteaux J-C, Clodic G, Duchet M, Simoneau A, Platzer MF. Techno-economic feasibility of fleets of far offshore hydrogen-producing wind energy converters. Int J Hydrogen Energy 2018;43:7266–89. https://doi.org/10.1016/j.ijhydene.2018.02.144.

[54] Pua C, Hu P, Ji C, Zhu Z, Zheng B, Zhai S. Simulation analysis of protective wall against hydrogen combustion from liquified hydrogen storage tank on the offshore launching platform. Int J Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2022.12.120.

[55] Ustolin F, Campari A, Taccani R. An extensive review of liquid hydrogen in transportation with focus on the maritime sector. J Mar Sci Eng 2022;10. https://doi.org/10.3390/jmse10091222.
[56] Yuan W, Li J, Zhang R, Li X, Xie J, Chen J. Numerical investigation of the leakage and explosion scenarios in China's first liquid hydrogen refueling station. Int J Hydrogen Energy 2022;47:18786–98. https://doi.org/10.1016/j.ijhydene.2022.04.060.
[57] Peschka W. Liquid hydrogen fuel of the future. New York: Springer-Verlag; 1992.
[58] Australian government. Australia exports world's first shipment of liquified hydrogen to Japan. Available online, https://www.austrade.gov.au/international/invest/investor-updates/australia-exports-world-s-first-shipment-of-liquified-hydrogen-to-japan. [Accessed 4 July 2022].
[59] Paul S. World's first hydrogen tanker to ship test cargo to Japan from Australia. Available online, https://www.reuters.com/business/environment/worlds-first-hydrogen-tanker-ship-test-cargo-australia-japan-2022-01-20/. [Accessed 3 June 2022].
[60] C-Job. LH2 Europe & C-job liquid hydrogen tanker. Available online, https://c-job.com/projects/liquid-hydrogen-tanker/. [Accessed 6 July 2022].
[61] Kamiya S. World's first ocean going liquid hydrogen carrier. Japan: Kawasaki Heavy Industries. Ltd.; 2019. p. 6–11. https://hysafe.info/wp-content/uploads/sites/3/2021/05/2_1_LH2-carrier-KHI-kamiya-for-publishing-1-1.pdf.
[62] Walia I. Ammonia hype builds in shipping market. Available online, https://lloydslist.maritimeintelligence.informa.com/LL1137516/Ammonia-hype-builds-in-shipping-market. [Accessed 15 October 2022].
[63] IRENA. Global hydrogen trade to meet the 1.5°C climate goal part II technology review of hydrogen carriers. Abu Dhabi. 2022.
[64] Methanex. Methanol as a Marine Fuel. Available online, https://www.methanex.com/about-methanol/methanol-marine-fuel. [Accessed 22 July 2022].
[65] Ellis J, Ólafsson M, Olsson T, Dolan G, Yalcin A, Jonkers P, et al. Methanol supply, bunkering guidelines, and infrastructure. the FASTWATER Consortium. 2021. p. 15–6.
[66] Jeyaseelan T, Ekambaram P, Subramanian J, Shamim T. A comprehensive review on the current trends, challenges and future prospects for sustainable mobility. Renew Sustain Energy Rev 2022;157:112073. https://doi.org/10.1016/j.rser.2022.112073.
[67] Prevljak NH. Maersk unveils design of next-gen methanol-powered boxships. Available online, https://www.offshore-energy.biz/maersk-unveils-design-of-next-gen-methanol-powered-containerships/. [Accessed 7 July 2022].
[68] Prevljak NH. CMA CGM orders its first methanol-powered containerships. Available online, https://www.offshore-energy.biz/cma-cgm-orders-its-first-methanol-powered-containerships/. [Accessed 7 July 2022].
[69] Huang J, Fan H, Xu X, Liu Z. Life cycle greenhouse gas emission assessment for using alternative marine fuels: a very large crude carrier (VLCC) case study. J Mar Sci Eng 2022;10:1969. https://doi.org/10.3390/jmse10121969.
[70] Niermann M, Drünert S, Kaltschmitt M, Bonhoff K. Liquid organic hydrogen carriers (LOHCs) – techno-economic analysis of LOHCs in a defined process chain. Energy Environ Sci 2019;12:290–307. https://doi.org/10.1039/C8EE02700E.
[71] Andersson J, Krüger A, Grönkvist S. Methanol as a carrier of hydrogen and carbon in fossil-free production of direct reduced iron. Energy Convers Manag X 2020;7:100051. https://doi.org/10.1016/j.ecmx.2020.100051.
[72] Prevljak NH. NYK: world's 1st global hydrogen supply chain demonstration project starts. Available online, https://www.offshore-energy.biz/nyk-worlds-1st-transocean-shipment-of-hydrogen-begins/. [Accessed 8 June 2022].
[73] Australian government. Funding available for clean hydrogen industrial hubs. Available online, https://www.dcceew.gov.au/about/news/funding-available-for-clean-hydrogen-industrial-hubs. [Accessed 18 August 2022].
[74] Albrecht U, Bünger U, Michalski J, Raksha T, Wurster R, Zerhusen J. International hydrogen, strategies; Ottobrunn, Germany: Ludwig-Bölkow-Systemtechnik GmbH; 2020. p. 36–42.
[75] IEA. Hydrogen projects database. Available online. https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database. [Accessed 28 June 2022].
[76] IEA. Net Zero by 2050: a Roadmap for the global energy sector. Int Energy Agency; 2021. p. 1.
[77] IEA. Global hydrogen review 2021. Int Energy Agency 2021:20–45.
[78] Pendlebury R, Meares T, Tyrrell J. Hydrogen: the new Australian manufacturing export industry and the implications for the National Electricity Market (NEM). https://www.aemc.gov.au/hydrogen-new-australian-manufacturing-export-industry-and-implications-national-electricity-market. [Accessed 4 July 2022].
[79] COAG Energy Coucil. Australia's National Hydrogen Strategy. 2019. p. 71.
[80] CSIRO. HyResource. 2021.
[81] Australian government. State of hydrogen. 2021.
[82] Argus. Australia's Geelong port to spend A$100mn on hydrogen. Available online, https://www.argusmedia.com/news/2278410-australias-geelong-port-to-spend-a100mn-on-hydrogen?amp=1. [Accessed 6 July 2022].
[83] Atchison J. 6 GW green export project planned for South Australia. Available online, https://www.ammoniaenergy.org/articles/6-gw-green-export-project-planned-for-south-australia/. [Accessed 25 July 2022].
[84] ARENA. Exploring renewable hydrogen opportunities at the Port of Newcastle. Available online, https://arena.gov.au/news/exploring-renewable-hydrogen-opportunities-at-the-port-of-newcastle/. [Accessed 4 July 2022].
[85] Milne P. Billions to transform the Pilbara: WA's hydrogen hubs plan revealed. Available online, https://www.watoday.com.au/politics/western-australia/billions-to-transform-the-pilbara-wa-s-hydrogen-hubs-plan-revealed-20220113-p59o1b.html. [Accessed 6 July 2022].
[86] Tasmanian Government. DRAFT Tasmanian Renewable Hydrogen Action Plan. 2019. p. 5–13.
[87] Williams A. NT government announces Darwin hydrogen hub project. Available online, https://www.thedcn.com.au/news/bulk-trades-shipping/nt-government-announces-darwin-hydrogen-hub-project/. [Accessed 18 August 2022].
[88] Port of Rotterdam. First exports of hydrogen from South Australia to Rotterdam feasible this decade. Available online, https://www.portofrotterdam.com/en/news-and-press-releases/first-exports-of-hydrogen-from-south-australia-to-rotterdam-feasible-this. [Accessed 13 July 2022].
[89] Queensland Government. Europe's largest port wants slice of Queensland hydrogen. Available online, https://statements.qld.gov.au/statements/93495. [Accessed 4 July 2022].
[90] Port of Rotterdam. Western Australia and Port of Rotterdam to collaborate on renewable hydrogen. Available online, https://www.portofrotterdam.com/en/news-and-press-releases/western-australia-and-port-of-rotterdam-to-collaborate-on-renewable. [Accessed 4 July 2022].

[91] Tasmanian Government. Tasmania and Port of Rotterdam sign green hydrogen MOU. Available online, https://www.premier.tas.gov.au/site_resources_2015/additional_releases/tasmania_and_port_of_rotterdam_sign_green_hydrogen_mou. [Accessed 4 July 2022].
[92] Government of Chile. National green hydrogen strategy. Santiago: Chile; 2020.
[93] Whitlock R. Chile seeking green hydrogen export corridor to Europe. Available online, https://www.renewableenergymagazine.com/hydrogen/chile-seeking-green-hydrogen-export-corridor-to-20220113. [Accessed 5 July 2022].
[94] Biogradlija A. Port of San Antonio to develop green hydrogen plant for its operations. Available online, https://energynews.biz/port-of-san-antonio-to-develop-green-hydrogen-plant-for-its-operations/. [Accessed 19 October 2022].
[95] Energyvoice. Mauritania sets out strategic path to hydrogen. Available online, https://www.energyvoice.com/renewables-energy-transition/hydrogen/africa-hydrogen/414222/mauritania-chariot-hydrogen-nour/. [Accessed 14 November 2022].
[96] S&P Global. Africa-focused Chariot inks green hydrogen import MOU with Port of Rotterdam. Available online, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/040622-africa-focused-chariot-inks-green-hydrogen-import-mou-with-port-of-rotterdam. [Accessed 4 July 2022].
[97] Esau I. Mauritania: chariot's green hydrogen project clinches deal with Rotterdam port. Available online, https://www.upstreamonline.com/energy-transition/mauritania-chariots-green-hydrogen-project-clinches-deal-with-rotterdam-port/2-1-1197885. [Accessed 19 October 2022].
[98] Nakano J. Saudi Arabia's hydrogen industrial strategy. Available online, https://www.csis.org/analysis/saudi-arabias-hydrogen-industrial-strategy.
[99] Brown T. Saudi Arabia ships low-carbon ammonia to Japan. Available online, https://www.ammoniaenergy.org/articles/saudi-arabia-ships-low-carbon-ammonia-to-japan/. [Accessed 4 July 2022].
[100] KASPSARC. Saudi Arabia bets big on blue hydrogen. Available online, https://www.kapsarc.org/news/saudi-arabia-bets-big-on-blue-hydrogen/. [Accessed 6 July 2022].
[101] Qamar Energy. Hydrogen in the GCC: a report for the regional business development team gulf region. The Hague 2020.
[102] The Norwegien Goverment. The Norwegian Government's hydrogen strategy-towards a low emission society. 2020.
[103] Husomanovic N. Norway targets 30 GW offshore wind by 2040, with hydrogen exports. Available online, https://energynews.biz/norway-targets-30-gw-offshore-wind-by-2040-with-hydrogen-exports/. [Accessed 16 August 2022].
[104] Pekic S. Green Hydrogen Systems electrolysis picked for Norway's H2 project. Available online, https://www.offshore-energy.biz/green-hydrogen-systems-for-norways-h2-project/. [Accessed 16 August 2022].
[105] Wettengel J. Imports to cover about half of EU's hydrogen needs by 2050 – report. Available online, https://www.cleanenergywire.org/news/imports-cover-about-half-eus-hydrogen-needs-2050-report. [Accessed 13 July 2022].
[106] BMWK. The national hydrogen strategy. 2020. Berlin.
[107] Bateman J. Hydrogen import-export partnerships "booming" around the world. Available online, https://www.cleanenergywire.org/news/hydrogen-import-export-partnerships-booming-around-world. [Accessed 5 July 2022].
[108] Macdonald-Smith A, Eyers J. Germany wants Australian hydrogen within three years. Available online, https://www.afr.com/companies/energy/how-hydrogen-will-reshape-energy-trade-routes-20220914-p5bhvz. [Accessed 25 October 2022].
[109] Hamburg Green Hydrogen Hub. Available online, https://www.hghh.eu/en. [Accessed 13 July 2022].
[110] Radowitz B. Germany plans to import hydrogen from UAE using 'liquid organic carrier' technology. Available online, https://www.rechargenews.com/energy-transition/germany-plans-to-import-hydrogen-from-uae-using-liquid-organic-carrier-technology/2-1-1188575. [Accessed 25 October 2022].
[111] Government of the Netherlands. Government strategy on hydrogen. 2020.
[112] Jones JS. Port of Rotterdam ups 2030 hydrogen supply to 4.6Mt. Available online, https://www.enlit.world/hydrogen/port-of-rotterdam-ups-2030-hydrogen-supply-to-4-6mt/. [Accessed 14 November 2022].
[113] New Zealand Goverment. The Netherlands looks to move from Russian gas to green hydrogen - june 2022. Available online, https://www.mfat.govt.nz/en/trade/mfat-market-reports/market-reports-europe/the-netherlands-looks-to-move-from-russian-gas-to-green-hydrogen-june-2022/. [Accessed 26 September 2022].
[114] HM Government. UK hydrogen strategy. 2021.
[115] Committee on Climate Change. Net Zero: the UK's contribution to stopping global warming. 2019.
[116] Frontier Economics. Business models for low carbon hydrogen production. 2020.
[117] Port of Cromarty Firth. Port of cromarty Firth signs historic green hydrogen MoU with Norwegian clean energy firm Gen2 energy AS. Available online, https://pocf.co.uk/2021/05/24/post-entry-a/. [Accessed 16 August 2022].
[118] UK Government. UK hydrogen export capability guide. Available online, https://www.gov.uk/government/news/uk-hydrogen-export-capability-guide. [Accessed 4 July 2022].
[119] Ministerial council on renewable energy hydrogen and related issues. Basic Hydrogen Strat. 2017. p. 1–33.
[120] Nakano J. Japan's hydrogen industrial strategy. Available online, https://www.csis.org/analysis/japans-hydrogen-industrial-strategy. [Accessed 27 July 2022].
[121] Ogawa K. Japan taps Australia and Brunei for hydrogen import goal. Available online, https://asia.nikkei.com/Business/Energy/Japan-taps-Australia-and-Brunei-for-hydrogen-import-goal. [Accessed 5 July 2022].
[122] CMS. Hydrogen law and regulation in Japan. Available online, https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/japan. [Accessed 24 July 2022].
[123] Argus. Japan's Kobe port exploring future hydrogen potential. Available online, https://www.argusmedia.com/en/news/2214597-japans-kobe-port-exploring-future-hydrogen-potential. [Accessed 6 July 2022].
[124] Argus. Japan Onahama port to examine ammonia, hydrogen imports. Available online, https://www.argusmedia.com/en/news/2202370-japan-onahama-port-to-examine-ammonia-hydrogen-imports. [Accessed 6 July 2022].
[125] METIE. Hydrogen economy roadmap of Korea. 2019.
[126] S&P Global. S Korea to provide 27.9 mil mt/year of 'clean hydrogen' by 2050. Available online, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/112621-s-korea-to-provide-279-mil-mtyear-of-clean-hydrogen-by-2050. [Accessed 5 July 2022].
[127] Queensland Government. Port builds North Queensland's hydrogen future. Available online, https://statements.qld.gov.au/statements/93136. [Accessed 6 July 2022].
[128] Min-hee J. Hydrogen developers divided into ammonia and liquid hydrogen advocates. Available online, http://www.

businesskorea.co.kr/news/articleView.html?idxno=78432. [Accessed 24 July 2022].
[129] Australian government. Australia and Korea partnering on clean energy. Available online, https://www.austrade.gov.au/news/media-releases/australia-and-korea-partnering-on-clean-energy. [Accessed 5 July 2022].
[130] Ulsan metropolitan city. Ulsan to be transformed into logistical hub of green hydrogen. Available online, https://www.investkorea.org/us-en/bbs/i-1426/detail.do?ntt_sn=491223. [Accessed 6 July 2022].
[131] MTI. Singapore's national hydrogen strategy. 2022. Singapore.
[132] Statista. Total bunker sales in Singapore from 2012 to 2021. Available online, https://www.statista.com/statistics/870575/singapore-bunker-sales/. [Accessed 1 August 2022].
[133] DNV. *Hydrogen Forecast to 2050: energy transition outlook 2022*. Norway: Høvik; 2022.
[134] Australia partners with Singapore on hydrogen in maritime sector. Available online, https://www.minister.industry.gov.au/ministers/taylor/media-releases/australia-partners-singapore-hydrogen-maritime-sector. [Accessed 3 June 2022].
[135] Matich B. Singapore sovereign wealth fund backs Australian green hydrogen developer. Available online, https://www.pv-magazine.com/2022/01/27/singapore-sovereign-wealth-fund-backs-australian-green-hydrogen-developer/. [Accessed 13 July 2022].
[136] Lewis J. Origin and MOL explore shipping green ammonia from Australia from 2026. Available online, https://www.upstreamonline.com/hydrogen/origin-and-mol-explore-shipping-green-ammonia-from-australia-from-2026/2-1-1050647. [Accessed 25 July 2022].
[137] NYK Line. World's first global hydrogen supply chain demonstration project starts in earnest. Available online, https://www.nyk.com/english/news/2020/20200625_01.html.
[138] Marubeni. HySTRA celebrates completion of world's first liquefied hydrogen vessel voyage in Japan. Available online, https://www.marubeni.com/en/news/2022/release/00030.html. [Accessed 16 August 2022].
[139] Krasae-in S, Stang JH, Neksa P. Development of large-scale hydrogen liquefaction processes from 1898 to 2009. Int J Hydrogen Energy 2010;35:4524–33. https://doi.org/10.1016/j.ijhydene.2010.02.109.
[140] Inomata A, Hashimoto S, Yamanouchi K, Yamamoto T. Hydrogen storage — development of liquefied hydrogen terminal. Kawasaki Tech Rev 2021:29–34.
[141] Ratnakar RR, Gupta N, Zhang K, van Doorne C, Fesmire J, Dindoruk B, Balakotaiah V. Hydrogen supply chain and challenges in large-scale LH2 storage and transportation. Int J Hydrogen Energy 2021;46:24149–68. https://doi.org/10.1016/j.ijhydene.2021.05.025.
[142] Port of Rotterdam. Hydrogen comes in different 'packages'. 2022. p. 1–3.
[143] WCN. Air Products, Gunvor to build hydrogen import terminal in Rotterdam port. Available online, https://www.worldconstructionnetwork.com/news/air-products-gunvor-to-build-hydrogen-import-terminal-in-rotterdam-port. [Accessed 12 July 2022].
[144] Macdonald-Smith A. Origin inks accord for hydrogen exports from Townsville. Available online, https://www.afr.com/companies/energy/origin-inks-accord-for-hydrogen-exports-from-townsville-20210414-p57j2c. [Accessed 25 July 2022].
[145] Ewing R. Australia's TasPorts signs deal to progress green hydrogen project. Available online, https://www.icis.com/explore/resources/news/2021/06/22/10654934/australia-s-tasports-signs-deal-to-progress-green-hydrogen-project/. [Accessed 25 July 2022].
[146] ABEL. Bell Bay powerfuels project. Available online, https://www.abelenergy.com.au/our-projects. [Accessed 25 July 2022].
[147] Wettengel J. RWE aims to make LNG import terminal hydrogen-ready with green ammonia. Available online, https://www.cleanenergywire.org/news/rwe-aims-make-lng-import-terminal-hydrogen-ready-green-ammonia. [Accessed 3 June 2022].
[148] Radowitz B. Uniper resumes plans for 'hydrogen-ready' German LNG terminal: fortum CEO. Available online. https://www.rechargenews.com/energy-transition/uniper-resumes-plans-for-hydrogen-ready-german-lng-terminal-fortum-ceo/2-1-1179191. [Accessed 3 June 2022].
[149] Fotis Rigas TA. Hydrogen safety. Boca Raton: CRC Press; 2013.
[150] Jeehyun LS-hC. Tank explosion poses setback for Seoul's push for hydrogen economy. Available online, https://pulsenews.co.kr/view.php?year=2019&no=346776. [Accessed 8 June 2022].
[151] IMO. Interim recommendations for carriage of liquefied hydrogen in bulk (RESOLUTION MSC.420(97)). 2016. p. 6–7.
[152] Pritchard DK, Rattigan WM. Hazards of liquid hydrogen (RR769 Research Report). UK: the Health and Safety Laboratory; 2010. p. 2–7.
[153] NASA. Safety standard for hydrogen and hydrogen systems: guidelines for hydrogen system design, materials selection, operations, storage, and transportation. 1997.
[154] Godula-Jopek A, Jehle W, Wellnitz Jr. Hydrogen storage technologies: new materials, transport, and infrastructure. Weinheim, Germany: WILEY-VCH; 2012.
[155] Odsæter LH, Skarsvåg HL, Aursand E, Ustolin F, Reigstad GA, Paltrinieri N. Liquid hydrogen spills on water—risk and consequences of rapid phase transition. Energies 2021;14:4789.
[156] Ordin PM. Review of hydrogen accidents and incidents in NASA operations; national Aeronautics and space administration. 1974.
[157] Lowesmith BJ, Hankinson G, Chynoweth S. Safety issues of the liquefaction, storage and transportation of liquid hydrogen: an analysis of incidents and HAZIDS. Int J Hydrogen Energy 2014;39:20516–21. https://doi.org/10.1016/j.ijhydene.2014.08.002.
[158] Kurtz J, Sprik S, Bradley TH. Review of transportation hydrogen infrastructure performance and reliability. Int J Hydrogen Energy 2019;44:12010–23. https://doi.org/10.1016/j.ijhydene.2019.03.027.
[159] SIGTTO. Liquefied gas handling principles on ships and in terminals (LGHP4); Witherby. Livingston: Scotland; 2016.
[160] Halfhid R. Is ammonia set to be the best route towards decarbonisation? Green shipping 2021-A supplement to the Naval Architect 2021:24–5.
[161] Bicer Y, Dincer I. Environmental impact categories of hydrogen and ammonia driven transoceanic maritime vehicles: a comparative evaluation. Int J Hydrogen Energy 2018;43:4583–96. https://doi.org/10.1016/j.ijhydene.2017.07.110.
[162] Fahnestock J, Søgaard K, Lawson E, Kilemo H. NoGAPS: Nordic Green Ammonia Powered Ship. 2021. p. 18–20.
[163] Quest. Comparative quantitative risk analysis of motor gasoline, LPG, and anhydrous ammonia as an automotive fuel. Quest Consultants Inc; 2009. p. 41–53.
[164] de Vries N. Safe and effective application of ammonia as a marine fuel. master thesis. Delft, The Netherlands: Delft University of Technology; 2019.
[165] Hansson J, Brynolf S, Fridell E, Lehtveer M. The potential role of ammonia as marine fuel—based on energy systems modeling and multi-criteria decision analysis. Sustainability 2020;12:3265. https://doi:10.3390/su12083265.

[166] IMO. Methanol as marine fuel: environmental benefits, technology readiness, and economic feasiblity. London, UK. 2016.
[167] SHIPPING AUSTRALIA. Methanol – a strong contender. 2021. p. 58–60.
[168] Wang S, Zhu J. Test of metal corrosion by methanol and methanol-gasoline. In proceedings of the 2010 international conference on advances in energy engineering2010; June 2010. p. 27–30. 19-20.
[169] Methanol Institute. Compatibility of Metals & Alloys in Neat Methanol Service. 2016. p. 1–15.
[170] Schönauer A-L, Glanz S. Hydrogen in future energy systems: social acceptance of the technology and its large-scale infrastructure. Int J Hydrogen Energy 2022;47:12251–63. https://doi.org/10.1016/j.ijhydene.2021.05.160.
[171] Itaoka K, Saito A, Sasaki K. Public perception on hydrogen infrastructure in Japan: influence of rollout of commercial fuel cell vehicles. Int J Hydrogen Energy 2017;42:7290–6. https://doi.org/10.1016/j.ijhydene.2016.10.123.
[172] Lozano LL, Bharadwaj B, de Sales A, Kambo A, Ashworth P. Societal acceptance of hydrogen for domestic and export applications in Australia. Int J Hydrogen Energy 2022;47:28806–18. https://doi.org/10.1016/j.ijhydene.2022.06.209.
[173] Guati-Rojo A, Demski C, Valera-Medina A. Chapter 12-beyond the technology: public perception of ammonia energy technologies. In: Valera-Medina A, Banares-Alcantara R, editors. Techno-economic challenges of green ammonia as an energy vector. Academic Press; 2021. p. 277–302.
[174] Bergman N, Axup K, Johnstone E, Simpson R. Hydrogen is here - are you ready?. Available online, https://www.allens.com.au/insights-news/insights/2021/08/hydrogen-is-here-are-you-ready/#Footnotes. [Accessed 24 July 2022].
[175] Rowell J, Bergman N, Asedy HA, Simpson R. The down low on hydrogen policy and regulation in Australia. Aust Environ Rev 2022:143–8.
[176] Standards Australia. Hydrogen standards release summary. Standards Australia; 2020. p. 1–2.
[177] Barros Sebastián, Barros LM. T. Hydrogen law, regulations & strategy in Chile. Available online, https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/chile. [Accessed 18 October 2022].
[178] Kordvani A, Salah F. Hydrogen law, regulations & strategy in the middle east. Available online, https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/middle-east. [Accessed 21 August 2022].
[179] Hasaas O, Madland SV, Skrunes S. Hydrogen law, regulations & strategy in Norway. Available online, https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/norway. [Accessed 18 October 2022].
[180] European Parliament. EU directive on gas and hydrogen networks. 2022. p. 1–6.
[181] Ertug I. Revision of the directive on deployment of alternative fuels infrastructure. Available online, https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-revision-of-the-directive-on-deployment-of-alternative-fuels-infrastructure. [Accessed 24 July 2022].
[182] United Nations. ADR 2023-Agreement concerning the international carriage of dangerous Goods by road. 2022.
[183] Wurster R, Hof E. The German hydrogen regulation, codes and standards roadmap. Int J Energy Res 2021;45:4835–40. https://doi.org/10.1002/er.6249.
[184] Majunder-Russell D, Rihoy C, Mitchell K. Hydrogen law, regulations & strategy in the United Kingdom. Available online, https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/united-kingdom. [Accessed 12 January 2023].
[185] Song Z. Hydrogen law and regulation in South Korea. Available online, https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/south-korea. [Accessed 24 July 2022].
[186] Rathbone M, Wong A, Quek J. Hydrogen law and regulation in Singapore. Available online, https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/singapore. [Accessed 24 July 2022].
[187] PWC. National hydrogen skills and training analysis. Available online, https://www.skillsforaustralia.com/hydrogen-2/. [Accessed 24 July 2022].
[188] HSE. Safe net zero 2021-hydrogen. Available online, https://www.hsl.gov.uk/health-and-safety-training-courses/safe-net-zero-2021–-hydrogen?cg=21674. [Accessed 22 August 2022].
[189] Ffooks R. Natural gas by sea: the development of a new technology. London, UK: Witherby & Co. Ltd.; 1993. p. 245.
[190] GIIGNL. GIIGNL annual report. 2022.
[191] Donnelly J. Qingdao Port becomes the world's first hydrogen-powered and 5G intelligent port. Available online, https://www.porttechnology.org/news/qingdao-port-becomes-the-worlds-first-hydrogen-powered-and-5g-intelligent-port/. [Accessed 27 July 2022].
[192] WPSP. Port of Yokohama – hydrogen supply chain joint study. Available online, https://sustainableworldports.org/project/port-of-yokohama-hydrogen-supply-chain-joint-study/. [Accessed 3 June 2022].
[193] Ports of Auckland. Ports of Auckland to build Auckland's first hydrogen production and refuelling facility. Available online, https://www.poal.co.nz/media/ports-of-auckland-to-build-auckland%E2%80%99s-first-hydrogen-production-and-refuelling-facility. [Accessed 27 July 2022].
[194] Port of Antwerp. Hydrogen-powered tug is world first for Port of Antwerp. Available online, https://newsroom.portofantwerpbruges.com/hydrogen-powered-tug-is-world-first-for-port-of-antwerp. [Accessed 27 July 2022].
[195] Container News. Port of Rotterdam plans to enable 1,000 hydrogen trucks on the European roads. Available online, https://container-news.com/port-of-rotterdam-plans-to-enable-1000-hydrogen-trucks-on-the-european-roads/. [Accessed 6 September 2022].
[196] Husomanovic N. First hydrogen tractor tested at Port of Valencia. Available online, https://energynews.biz/first-hydrogen-tractor-tested-at-port-of-valencia/. [Accessed 6 September 2022].
[197] Lovrakon T. Hino to join hydrogen demo study in California ports. Available online, https://www.fleetequipmentmag.com/hino-hydrogen-demo-study/. [Accessed 6 September 2022].
[198] Derwent R, Simmonds P, O'Doherty S, Manning A, Collins W, Stevenson D. Global environmental impacts of the hydrogen economy. Int J Nucl Hydrogen Prod Appl 2006;1:57–67. https://10.1504/ijnhpa.2006.009869.
[199] Plimer I. Climate change delusion and the Great electricity rip-off; connor court publishing pty ltd Australia. 2017.