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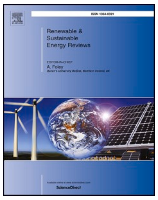

The role of hydrogen as enabler of industrial port area decarbonization

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ABSTRACT

To meet environmental goals while maintaining economic competitiveness, worldwide ports have increased the amount of renewable energy production and have focused in optimizing performances and energy efficiency. However, carbon-neutral operation of industrial port areas (IPA) is challenging and requires the decarbonization of industrial processes and heavy transport systems. This study proposes a comprehensive review of decarbonization strategies for IPA, with a particular focus on the role that green hydrogen could play when used as renewable energy carrier. Much information on existing and future technologies was also derived from the analysis of 74 projects (existing and planned) in 36 IPAs, 80 % of which are in Europe, concerning hydrogen-based decarbonization strategies. The overall review shows that engine operation of ships at berth are responsible of more than 70 % of emissions in ports. Therefore, onshore power supply (OPS) seems to be one of the main strategies to reduce port pollution. Nevertheless, OPS powered by hydrogen is not today easily achievable. By overcoming the current cost-related and regulation barriers, hydrogen can also be used for the import/export of green energy and the decarbonization of hard-to-abate sectors. The technical and economic data regarding hydrogen-based technologies and strategies highlighted in this paper are useful for further research in the field of definition and development of decarbonization strategies in the IPA.

1. Introduction

Shipping and ports play a central role in global trade and economy by managing the 80 % of the whole worldwide commerce in terms of volume and the 70 % of its total value [1]. Although ports promote regional economic and technological development, they have an environmental impact on their surroundings, which is especially reflected in terms of reduced air quality. Populated coastal areas and port cities are subjected to large amounts of green-house gases (GHG), pollutants and particular matter emissions. By further considering that the 40 % of global population is settled within 100 km from the coastline and that half of the global tourism develops in coastal areas [2], it is clear as the impact of ports and shipping pollution represents an important health and social issue. By focusing to the port-level, ship traffic is responsible for more than the 70 % of the total gaseous emissions, while the remnant emissions derive from port equipment, buildings and from industrial sectors interconnected to port-related activities [3,4].

Industrial port areas (IPA) can be characterized as a comprehensive system comprising of ports and industries related to them. Historically, ports have served as a means for facilitating trade and supplying materials and energy [5]. In the foreseeable future, it is anticipated that ports will also assume a new function as renewable energy hubs [6,7]. In this regard, and with respect to the decarbonization targets set within the European Green Deal, IPA could significantly contribute to the transition towards greener economies. The European Union (EU) considers hydrogen as one of the main pillars to be integrated in the future energy systems and it is often proposed as a promising option for decarbonizing IPA. For instance, a target of 10 million tons of domestic renewable hydrogen production and 10 million tons of imports by 2030 has been set as one of the main goals to be reached within the REPowerEU plan [8]. Green hydrogen can be also the keystone for coupling different industrial and economic sectors, such as maritime, oil and gas, cruise-based-tourism, bulk distribution and transformation, thermal power plants, electricity grid operators and offshore wind, which are typically hosted in port areas [5,9].

The concept of sustainability applied to ports and port cities has been recently started to be discussed: Zheng et al. [10] focused their review on the sustainability of port cities, with the aim to shed light to propose new research directions to be followed in the next years, emphasising

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List of abbreviations

CHP	Combined heat and power
EU	European Union
FC	Fuel cells
GHG	Green-house gases
ICE	Internal combustion engines
IPA	Industrial port areas
LH_2	Liquified hydrogen
LNG	Liquified natural gas
NG	Natural gas
NH_3	Ammonia
OPS	Onshore power supply
RES	Renewable energy sources
TRL	Technology readiness level

the particular interest in sustainability in European port cities (about 54 % of studies are based on European ports), and highlighting the important role of research in defining strategies for implementing port sustainability. Moreover, Lim et al. [11] analysed the main measures to be taken to improve the sustainability of port area operations and management: several sustainability indicators defined in different studies were analysed, showing that environmental-addressed-research mainly focuses on pollution, social-addressed-research mainly focuses on human resources management and that economic-addressed-research mainly focuses on port management and frontier investments. Both works can be considered useful to obtain an overview of strategies to be followed when pursuing the aim of improving port sustainability. Although decarbonization is one of the most discussed topics for port sustainability, adoptable technologies and strategies were marginally addressed by these authors. Conversely, Alamoush et al. [12] reviewed 214 studies and classified all of the applicable measures mutually addressing to ships and ports into seven main categories and nineteen subcategories as a tool available for policymakers and researchers. In parallel, Iris et al. [13] classified a set of studies investigating port energy efficiency solutions into operational strategies, adoptable technologies (such as hybrid vehicles), and energy management systems (for example microgrids architecture). Differently, Sifakis et al. [14] analysed the feasibility of solutions for ports decarbonization depending on ports size (local, national and international ports). By combining the results of these three works, it can be highlighted that.

- port decarbonization in countries under development is poorly addressed [12], by considering that their weight could not to be neglected when considering decarbonization worldwide;
- any strategy adopted, if applied alone, is unlikely to lead to an effective port decarbonization [12];
- alternative energy management systems and technologies for ports decarbonization are currently underused due to their cost and low level of technological maturity [14];
- research can still have a fundamental role in finding new ways, optimizing, and spreading decarbonization strategies in ports, where decarbonization is still at its early stages [13];
- hydrogen can play an important role in decarbonising port activities both in the medium and in the long term [12–14].

More in depth, the role of hydrogen in port decarbonization have been recently investigated: Ortiz-Imedio et al. [15] evaluated the future hydrogen and electricity demands needed to power supply both freight and passenger transport along the Atlantic coast of Europe in 2050 with RES only, finding that hydrogen will be essential in guaranteeing a more sustainable maritime transportation on the European Atlantic coast. Kinnon et al. [16] focused on fuel cells (FC) application in ports, such as stationary power and heat generators, powertrains, and chemical fuel trigeneration. Their research was further addressed in analysing their particular advantages in microgrid-based systems. FC resulted to be a competitive technology in terms of energy conversion efficiency and emissions in comparison with the other technologies analysed: internal combustion engines (ICE), steam and gas turbines, and microturbines. In addition, trigeneration systems have the potential to maximise benefits, as they can simultaneously generate hydrogen, electricity and heat.

The present work is thus addressed to the operational strategies, technologies, and energy management systems which are currently available to reduce the GHG emissions and improve energy efficiency in ports and IPA. In this context (and to the authors' knowledge), a lack in literature is wanted to be filled, providing an in-depth analysis focused to the potential applications related to the hydrogen-based technologies. In this framework, this paper presents several novel contributions to the existing work in the literature. A comprehensive review of hydrogen-based decarbonization strategies for IPA is provided, emphasising the role of hydrogen and hydrogen-based technologies and comparing their main technical and economic characteristics. An essential aspect of this study lies in the enriched literature review, which also includes an extensive collection of projects concerning the current or future adoption of hydrogen in various IPA. Information provided by the authors not only serves to improve understanding of the challenges and potential solutions in terms of economic, energy and environmental implications, but also presents a perspective on the current economic, technological and regulatory barriers that need to be overcome to facilitate the widespread implementation of hydrogen technologies. The technical and economic data examined in this study can be beneficial for the advancement of research in the definition and development of decarbonization strategies in IPA.

This document is divided in three sections: (i) ***Decarbonization strategies of industrial port areas and the role of hydrogen-based technologies*** illustrates and emphasizes the use of hydrogen and hydrogen-based technologies in comparison to alternative options, by analysing the different options and their potential for reducing carbon emissions in IPA. In (ii) ***Analysis of hydrogen-related projects in worldwide ports***, an extensive analysis addresses the main feasibility studies, project proposals, and existing facilities related to the use of hydrogen for decarbonizing IPA, compared on a global scale. A complete dataset used for this analysis has been organized in the form of a spreadsheet file (Data_ports.xlsx), available in the Supplementary Material. Finally, in (iii) ***Concluding remarks and future trends,*** a critical analysis about strategies and tools available for port decarbonization is provided, highlighting technology gaps, and summarizing the main technical and economic barriers for the implementation of hydrogen-based technologies.

2. Decarbonization strategies of industrial port areas and the role of hydrogen-based technologies

The main decarbonization strategies adoptable by IPA to reduce their carbon emission footprint are here compared: advantages and disadvantages are discussed, together with their relevance and potential impact in terms of decarbonization. Particular attention is drawn to the potential role of hydrogen-based technologies and/or actions. Fundamental characteristics of these technologies have been summarized in Table 1. For each technology, investment costs, technology readiness level (TRL, determined according to the standards provided by the European Commission [17]), technological diffusion bottlenecks, decarbonization potential, and hydrogen demand are compared in Table 1. Potential applications of these technologies in the different decarbonization strategies presented in the following subsections are also indicated in the *Potential application* column. Strategies for energy efficiency improvement of buildings and lighting systems are not considered as not directly related to the hydrogen use.

Table 1
Characteristics of hydrogen-based technologies for IPA decarbonization.

Technology	Investment cost	TRL(a)	Bottlenecks	Decarbonization potential	Hydrogen demand	Potential application	General notes
FC for stationary applications [18,19]	2 ÷ 10 k€/kW	6 ÷ 8	- High costs - Small-scale applications - Limited stack lifetime	PP: 0.30(b) kg_{CO2}/kWh CHP: >0.20(b) kg_{CO2}/kWh	0.06 kg_{H2}/kWh_{el}	1. Onshore power supply	Investment costs for CHP-FC stationary applications are expected ranging in between 7 ÷ 10 k€/kW.
FC for ship propulsion(d) [20–22]	1.5 ÷ 4 k€/kW	6 ÷ 8	- Relatively low energy density of compressed and liquid hydrogen with respect conventional fuels - Reduced heat recovery possibility in PEM - Lack of standards for onboard FC installation	0.55(e) kg_{CO2}/kWh	0.06 kg_{H2}/kWh_{el}	2. Bunker fuels	Adopting solid oxide fuel cell technology instead of low-temperature proton exchange membrane one, would allow to facilitate heat recovery and, therefore, in some applications, reduce fuel consumption. However, their application is hampered by low TRL (4 ÷ 6) and higher costs (4 ÷ 7 k€/kW).
Hybrid hydrogen fuel cells vehicles and equipment [23–25]							
Forklifts	20 ÷ 25 k€/unit	7 ÷ 9	- High costs - Lacking hydrogen infrastructure - Lack of standards	93 kg_{CO2}/day(f)	5 kg_{H2}/day	3. Port logistics	Forklifts: already available in commerce. Yard tractors and reach stackers: only prototype available. Cranes: planned but not developed yet.
Yard tractors*	175 ÷ 250 k€/unit	6 ÷ 7-		392 kg_{CO2}/day(f)	21 kg_{H2}/day		
Reach stackers*	490 ÷ 700 k€/unit	6 ÷ 7		467 kg_{CO2}/day(f)	25 kg_{H2}/day		
Cranes*	2.5 ÷ 3.5 M€/unit	5 ÷ 6		840 kg_{CO2}/day(f)	45 kg_{H2}/day		
Electrolysers [26–29]							
Alkaline	0.5 ÷ 1.2 k€/kW	7 ÷ 9	- High costs - Limited stack lifetime	–	–	4. Power generation and storage from renewable energy sources 5. Import and export of energy	Solid-oxide technology allows to easily recover high temperature heat.
Acidic	1 ÷ 1.8 k€/kW	6 ÷ 9-		–	–		
Solid Oxide	1.2 ÷ 2 k€/kW	4 ÷ 7-		–	–		
Hydrogen refuelling stations [25,30,31]							
$CH_2^{(g)}$	0.5 ÷ 2 M€	6 ÷ 9	- High costs (in particular for refuelling heavy-duty vehicles) - Lack of demand - Lack of standards ruling their installation in IPA	–	–	3. Port logistics	Existing hydrogen refuelling stations (providing cH2) are mostly addressed to light-duty vehicles (cars, and forklifts). Lack of demand is mostly involving technologies using liquified hydrogen (LH_2).
$LH_2^{(h)}$*	1.5 ÷ 4 M€	5 ÷ 7-		–	–		
Hydrogen ship bunkering systems [21,32,33]							
$cH_2^{(g)}$*	1 ÷ 3 M€	4 ÷ 7	- High cost expected - Low TRL - Lack of demand - Lack of standards ruling their installation and use	–	–	2. Bunker fuels	No hydrogen bunkering systems are currently available.
$LH_2^{(h)}$*	2.5 ÷ 5 M€	4 ÷ 7-		–	–		

The table reports the characteristics of hydrogen technologies useable in IPA to decarbonize their activities. Investment costs for the solutions which are not commercially available yet, are indicated as an estimation retrieved from literature, and marked with (*). In Bottlenecks, the main issues hampering technological deployment are listed. Decarbonization potential is evaluated considering the use of zero-impact hydrogen, meaning it is produced and transported without any CO_2 emissions. Where possible, power production only (PP) or combined heat and power (CHP) production were separately considered. Hydrogen demand lists the required unitary hydrogen amount characterizing each technology. In *General notes* additional information is provided. Notes: (a) technology readiness level, low TRL means that only the basic principles of technology have been observed (low maturity), high TRL means that the technology has been proven in operational environment (high maturity); (b) power supplied via the grid within the EU; (c) fuel: natural gas, CHP engine efficiency: 90 %; (d) proton exchange membrane technology is taken as a reference; (e) fuel: marine diesel oil, engine efficiency: 50 %; (f) considering typical Diesel consumption of port vehicles and equipment; (g) gaseous compressed hydrogen stored within – 40 ÷ 80 °C at 700 bar; (h) liquified hydrogen stored at −253 °C, 1 bar.

2.1. *Onshore power supply*

Maritime traffic trend is growing worldwide: long-term economic and energy analysis, predicted as shipping emissions could rise up to 30 % in 2050 with respect to 2008 [34]; consequently, an increase from the maritime sector to the global GHG emissions (currently equal to 3 %) is expected. The shipping industry is considered to have relatively low emissions compared to rail and road transportation; however, the highest levels of pollutants are generated in port areas. This is because ships operating near coastlines are releasing lots of pollutants during manoeuvring, docking, undocking, loading, and unloading [35]. Moreover, when ships are docked, on-board power generators need to be kept active for powering air conditioning systems, pumps, control systems and cargo handling ones. As a result, docked-ship-related operations are responsible up to 70 % of the total emission of seaports in developed countries [14].

The onshore power supply (OPS, also known as cold ironing, shore-to-ship power supply, or shore-side electricity), consists in supplying power from a shore-side source to berthed ships, allowing them to switch-off on-board power generators, thus reducing noise and ship-related pollutant emissions. Although some OPS applications can be already found operating in Europe [36] and worldwide [37], their large-scale deployment has yet to take place [38,39]. The benefits of OPS are many and cover environmental and economic aspects: for example, Stolz et al. [40] estimated that implementation of OPS could cut up to 5 Mt_{CO2} in the 714 major ports in the European economic area and in the United Kingdom. Merk et al. [35] analysed the emissions of the 50 largest ports have a total external cost about 12 billion euro per year (only costs not associated to the market price of the goods and services were evaluated). Analogous studies highlighted as the use of OPS would allow to abate emission costs in the European sea area, from the actual ranges (90 US$ for CO_2 and 1850 ÷ 5950 US$ for nitrogen oxides, NO_X) to 10 ÷ 30 US$/$t_{CO2}$ and 540 ÷ 1600 US$/$t_{NOX}$. By side, adapting OPS in port infrastructures was found benefitting not only to the overall port economy, but also the social and the environmental sectors [39,41,42]. For instance it was calculated as external costs per abated ton of pollutants with OPS are lower than external costs of emissions generated by ships staying at quay with engine running [36,40]. Moreover (and referring to the Port of Piraeus), it was shown as the external costs derived from particulate emissions weight as the 61 % of the total costs associated to ships emissions [41].

In combination with fixed OPS infrastructure at berth, the development of mobile and floating platforms has been considered, either composed by hybrid FC/batteries systems [43], either by a barge mounting a FC powertrain for powering anchored ships [44]. Both designs result in a viable, efficient and low-emission option for powering the dynamic loads required by vessels while ensuring smooth operation of the FC stack.

Although OPS allows to locally reduce air and acoustic pollution, several barriers still hamper its large-scale deployment, and the main bottlenecks are represented by: a limited power capacity of port grids, high installation costs, local cost of electrical energy (to be supplied to the docked ships), and by different power supply specifications of the shore-side power system and the on-board ones [45]. Moreover, if the electric power provided by the port is not produced from renewable energy sources (RES), it is clear as the ship-related local-emission due to OPS are not completely avoided, but the emissions amount will be dependent on the on-shore power generation technology and fuel. In this regards, it was demonstrated as a wrong application of OPS could lead to larger overall emissions with respect of using on-board auxiliary engines [46,47], this increase, in terms of CO_2, can reach 20 % [48,49].

Thus, the main trend for reducing local and global emissions in IPA consists in coupling renewable power systems, electric port grid and OPS infrastructures [50,51]. Such a trade-off is estimated to persist until the energy generated from RES will be large enough for covering OPS energy demand. In particular, microgrid technologies emerged to be an efficient solution for coupling different RES, energy storage systems, and electric grids together with the OPS infrastructure (Fig. 1). A properly designed architecture, would give excellent flexibility and redundancy, and it would be easy to integrate with different energy storage devices, in spite of a consistent upfront investment in terms of equipment [3,52]. In microgrid topology, hydrogen could be used as energy vector for storing the excess of RES-produced energy, to compensate their intermittent and non-predictable operative conditions. The electrical power could be obtained by means of hydrogen-fuelled FC or ICE, as later detailed. FC should be preferred, because hydrogen-powered ICE still emit NO_X and can be lower in efficiency [53]. Alternative hydrogen-based conversion technologies are currently under development (such as hydrogen open cycle gas turbines and hydrogen combined cycle gas turbines), but they are not mature enough for large scale applications yet [54].

Techno-economic characteristics of stationary FC for powering OPS infrastructures are reported in Table 1. According to the adopted technology, FC would also allow to exploit heat recovery, for improving system efficiency and reducing pollutants emissions [55]. FC were demonstrated to be promising also in terms of heat recovery possibilities, showing high performance efficiencies in cogeneration or trigeneration operation modes. In particular, solid oxide and molten carbonate FC allow enhanced heat recovery with respect to proton exchange membrane FC, and are thus more promising to be used in high-efficiency cogeneration systems providing heat and power [56].

2.2. *Bunker fuels*

Another effective reduction of emissions in ports could be obtained by adopting alternative fuels for shipping [57]. To date, maritime transport relies on the use of ICE for ship propulsion fed with fossil fuels, such as heavy fuel oil and marine diesel oil. Although such systems can count on low costs and a solid know-how for their use and maintenance, they often exceed the emission limits set by the International Maritime

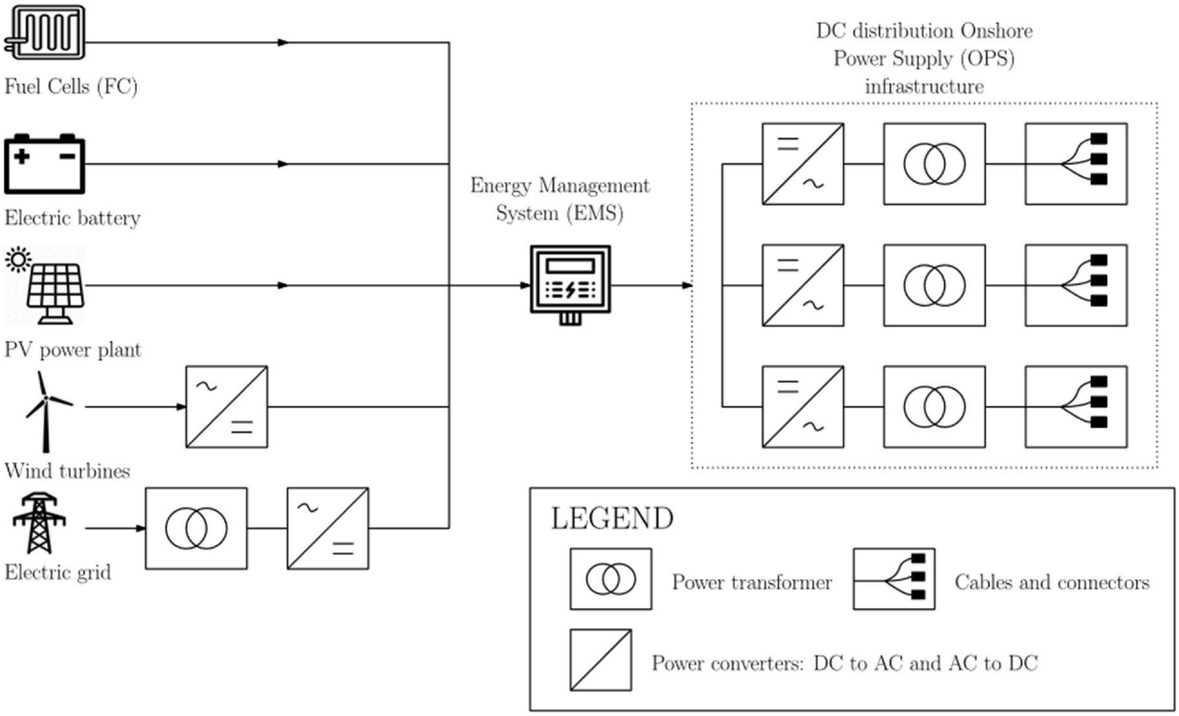

Fig. 1. Microgrid approach for OPS infrastructure. The concept of microgrid approach to power supply a direct current distribution OPS infrastructure is here sketched: hydrogen-fuelled FC, battery storage system, photovoltaic plant, wind turbines, and electric grid are here considered as possible power sources.

Organization (IMO) and national authorities, in particular during manoeuvring, docking, and stationing phases [58]. For example, a study conducted at the Busan container terminal in South Korea estimated that vessel manoeuvring is responsible for the 51 % of the total carbon emissions within the container terminal [59]. Shifting towards cleaner fuels could help in reducing emissions and promoting the deployment of transportation and bunkering infrastructure in ports, thus spreading the use of alternative fuels on a larger scale and fostering the emission reduction in ports on a wider perspective.

Bio-methanol can potentially guarantee the reduction of lifecycle NO_X emissions by up to 45 % and lifecycle SO_X emissions by up to 8 % with respect to conventional fuels [60]. Several fuels have been suggested for low or zero-emission shipping. An option currently in use, is represented by the liquified natural gas (LNG) [61]. Thanks to its chemical composition, LNG could ensure the navigation with almost zero emissions of SO_X and particular matter. Moreover, LNG could potentially cut the tank-to-propeller CO_2 emissions by up to 30 % when substituted to heavy fuel oils or marine diesel oils [62], even though the methane slip phenomenon could limit this result [63]. With 141 bunkering infrastructures already in use worldwide (bunker vessel, tank to ship, truck loading, bunker vessel loading, local storage, and others evaluated) and 56 planned ones, LNG bunkering can already rely on a branched infrastructural network [64]. In addition to LNG, biofuels were also proposed, as they could help in reducing both pollutants and GHG emissions, and can be produced using biomass. Among them, fatty acid methyl esters, hydrotreated vegetable oil, and biomass to liquid seem to be promising for maritime applications [65,66]. Although their production chain, in some cases, is still at the early stages of development, their chemical and physical properties are comparable to those of diesel fuel. Therefore, they could be directly used in conventional ICE in varying blending fractions and they could be well compatible for the existing bunkering services [65]. A further alternative is represented by methanol that is now mostly produced from NG [67], but it could also be produced from renewable feedstock (e.g. bio-methanol). Bio-methanol can potentially guarantee the reduction of lifecycle NO_X emissions by up to 45 % and lifecycle SO_X emissions by up to 8 % with respect to conventional fuels [60]. As for the bunkering, methanol can currently count on 117 operating bunkering stations worldwide [64]. Finally, ammonia (NH_3) has recently gained interest as a potential enabler of zero-local emissions in marine transportation [68]. NH_3 is produced from NG and it is widely used in several industrial processes. NH_3 could be potentially produced via carbon-emission-free processes powered by RES [69] and be directly used either in ICE or in FC. In the first case, it could potentially cut GHG emissions by 90 % with respect to heavy-fuel-oils-fed ICE [70], but additional post-combustion processing would be needed to curb NO_X emissions [71]. If used in FC, NH_3 could potentially achieve the goal of zero-local emissions propulsion as NO_X are not produced [70]. Nonetheless, on-board handling of NH_3 is still challenging due to safety issues and a bunkering infrastructure is still lacking, even if in the last years some projects were addressed to building a NH_3-dedicated bunkering network [72,73]. IPA could play a key role in enabling the use of NH_3 in shipping by hosting NH_3 storage systems and/or production centres [74]: in this way the maritime import/export of NH_3 would be facilitated, together with its use as chemical feedstock for decarbonizing the industrial processes included within IPA.

In this scenario, the interest on hydrogen as a potential alternative marine fuel is growing: thanks to its favourable characteristics for on-board marine applications (Table 1), it could guarantee a zero local emission navigation when used in FC [75], and ports could play a central role in establishing and sustaining the hydrogen demand for the maritime sector, not only by enabling an adequate bunkering infrastructure, but also by hosting production sites in port areas [76]. Several hydrogen ships have already been developed and are operating worldwide [77–79], but their widespread use is still limited by different issues. A first bottleneck is represented by the higher cost of hydrogen fuel and related technologies (e.g. FC, hydrogen-fuelled ICE, hydrogen tanks, bunkering infrastructure) compared to conventional fuels [80–83]. A second issue concerns hydrogen storage, because of the required larger storage volumes with respect fossil fuels [20,77]. Although such a problem could be more easily faced when dealing with small vessels operating in coastal areas [81,84], no adequate solutions based on compressed hydrogen (cH_2) have been found yet for bigger commercial and cruise ships [85]. In this framework, liquified hydrogen (LH_2) could represent a solution to be adopted by bigger ships for on-board storing, thanks to its higher energy density with respect to cH_2 [32]. As a third problem, a lack of regulation and standardization at the international level covering cH_2 and LH_2 handling, storage, bunkering, and use for shipping, can be highlighted. Conversely, rules and classification guidelines start to be available for the on-board FC installation and significant advancements are expected for the next years.

To conclude, compared to the conventional storage of marine diesel oil for shipping, cH_2 and LH_2 could adversely affect the performance of ships, leading to a lower range capability, a reduction in the cargo capacity allocated to containers or payloads in general, and higher capital expenditure of power system. Nonetheless, the normative lacks and discrepancies and the strict limitations currently ruling hydrogen storage and use in shipping, hydrogen still results the most suitable fuel to be used: having a high energy density, not being neither toxic (as NH_3 is) nor corrosive, and by potentially being carbon-neutral without additional carbon capture and storage plants (as needed for methanol). Moreover, hydrogen is also characterized by high energy efficiency from its production to its conversion into electrical power with respect to other energy vectors (e.g. methanol and NH_3) [71]. Finally, it should be considered as establishing a hydrogen supply chain for shipping could also open the door to a widespread use of hydrogen-based fuels to decarbonize other energy intensive energy sectors, such as heavy transport [86,87] or steel production (further details in *Section 6. Interplay with industries and port cities*), where full electrification (or application of electric storage systems) is not achievable.

2.3. Port logistics

Port logistics are used to allow intermodal transportation in between the three main port areas (quayside, yard side, landside – Fig. 2) and between ports areas and the inland. To date, logistics play a dominant role in shaping port key attributes fulfilling the desired trade-off between: (i) operation performance and attractiveness (i.e. depending on productivity, automation level, and connectiveness with distribution networks), (ii) compliance to EN16001 or ISO50001 (i.e. energy

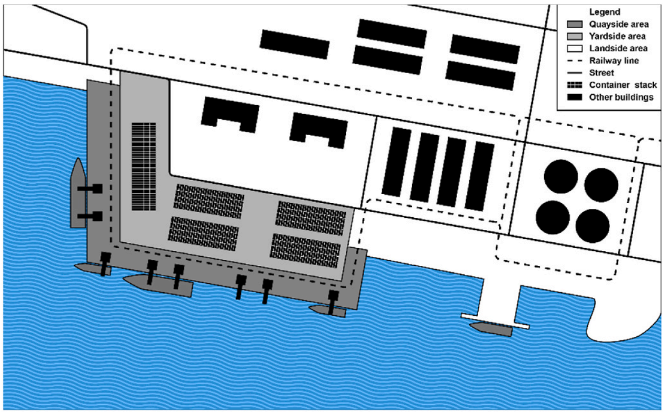

Fig. 2. Simplified schematic of a typical container terminal. Within port areas, goods and vehicles mainly operate in between quayside (dark grey), yard (light grey) and landside (white area). Transportation between port areas and the inland takes usually place by means of railway lines (dashed lines) and streets (solid lines).

efficiency improvement, RES-based energy production, energy management), (iii) compliance to ISO14001 (i.e. air and water systems management), (iv) economic competitiveness, and (v) safety and security [1,88–90]. Hydrogen-based technologies are expected to positively affect most of the previously listed attributes, especially in terms of energy efficiency and decarbonization potential [5], and improvements can be developed according to two different approaches [13,90].

With the first one, a port is considered as a whole, stand-alone system: port operational strategies are characterized and controlled with the aim of optimizing their management. Here, a promising action consists in improving the level of automation of both infrastructures and equipment, by introducing for example self-driving and/or autonomous lifting vehicles.

A second approach consists in installing and upgrading port equipment and infrastructures to the best available technologies, mostly involving the equipment dedicated to port cargo handling operations within quayside, yards and landside areas as well as with the management of inter-port logistics. To date, yard tractors, reach stackers, forklifts, cranes, and straddle carriers are commonly used in cargo handling areas [91], while quay cranes and ship-to-shore cranes are mostly used in the quayside for cargo handling [13,92]. On the yard side, rail-mounted gantry cranes, straddle carriers and reach stackers are commonly operating [93,94]. Inter-port transportation on land is usually based on heavy-good-vehicles, freight railways, while roll-on/roll-off cargo ships, tugboats, and barges ship across waterways. Nowadays, the equipment for cargo handling and inter-port vehicles (except for railways [29]) is almost entirely powered by oil-fuelled ICE and it was estimated as port equipment involved in cargo handling activities is responsible for up to 15 % of air emissions in port areas [52]. The replacement of ICE by using the best available technology can pass through three different paths: the adoption of alternative fuels, hybrid systems, and fully electrified ones. Fig. 3 shows some of the typical vehicles and equipment used in cargo handling areas and possible powertrain options.

2.3.1. *Alternative fuels*

Alternative fuels are able to guarantee carbon emissions reductions due to their low carbon content, to the low amount of impurities produced during combustion, and by evaluating their whole life cycle. To date, the most relevant options rely on natural gas (NG), biofuels, hydrogen, and synthetic fuels (such as NH_3 and methanol). NG combustion guarantees a reduction of both pollutants (such as NO_X) and CO_2 emission up to 30 % in comparison with traditional oil fuels, and it was proposed for light-duty equipment (yard tractors and reach stackers) [95] and heavy-good-vehicles too [96]. As a drawback, NG is currently affected by geopolitical turbulences and its price might be comparable with alternative fuels by 2050 [97]. The use of biofuels, such as biomethane and biodiesel, has already been tested in different ports worldwide [98]: they guarantee comparable energy densities with respect to traditional fuels, large availability and diversity of raw materials for production, storage simplicity, and are characterized by a reduced environmental impact [99]. Unfortunately, biofuels become critical when scaled up to a wide distribution level, due to extensive soil exploitation and to high production costs [100]. In parallel, although the use of hydrogen is more effective in FC, its direct use of in ICE has been tested since the early 2000s [101]. Further pilot applications based on ICE were recently developed: it is noteworthy to mention a locomotive for Canadian railways powered by a hydrogen-assisted hybrid system. When co-fuelled by NH_3 showed a potential CO_2 reduction up to 53 % with respect to conventional diesel fuel [102]. The ports of Hamburg and Bremerhaven tested a FC-powered forklift and hydrogen-fuelled ICE straddle carriers [13], respectively. A more flexible solution is proposed in the Port of Antwerp, where a tugboat powered by a dual fuel engine (diesel and hydrogen) is under construction [103]. The widespread deployment of hydrogen-based technologies and the establishment of a secure and efficient distribution chain are currently limited by the high hydrogen costs and by the difficulties connected to its on-board storage and handling. Storage issues are particularly affecting the maritime sector where vessel safety needs to be compliant to a strict regulation about both procedures and autonomy in navigation regime. In this context, NH_3 and methanol might represent more suitable solutions than hydrogen [104].

2.3.2. *Electrification*

In parallel to hydrogen-fuelled FC, also equipment electrification could lead to local zero emissions, coupled with a reduction of global emissions [14]. For instance, by means of life cycle assessment comparison between an ICE-powered yard tractors and their electrified counterparts, it resulted as the electrification of the 50 % of the yard tractor fleet operating within the Port of Los Angeles could reduce the pollutant emissions up to 60 % [105]. Moreover, the connection of rubber-tired gantry cranes to the grid was found reducing CO_2 emissions up to 80 % [106]. Regarding inter-port transportations, railways are the most electrified mean of transport, but in several circumstances convoys

Fig. 3. Typical vehicles and equipment used in cargo handling areas and possible powertrain options. Different types of commercial vehicles and equipment used for handling cargo in port areas are circled in blue. Different powertrain options for yard tractors are circled in green. These types of powertrains can also be used for the other vehicles and equipment operating in IPA (e.g. forklifts and reach stackers).

need to operate disconnected from the grid: some examples regard border crossing, service towards low populated areas, cargo handling on port branch lines or industrial spurs, or for maintenance purposes [29, 107]. In such situations, despite traction can be still supported by adopting batteries-based storage systems, batteries cannot cope with the daily energy demand especially when long working shifts are required or duty cycles peaking in power consumption as it happens with cranes and reach stackers. Swappable batteries seem a viable strategy to cover daily usage without recurring to oversize capacity installed on vehicle. Off-grid electrification via batteries-based storage systems is currently the main development paths for light good vehicles just as the overall road transportation sector (light-duty vehicles and passenger cars included) is driven towards electrification by a supportive policy framework [108].

2.3.3. *Hybridization*

ICE hybridization can remarkably mitigate local and global pollutant emissions by increasing powertrains efficiency via energy recovery and peak shaving [109]. Fuel/electric hybrids have high capabilities related to regenerative braking and peak shaving, where flexible electric storage systems are introduced (such as flywheels, ultracapacitors, and lithium-ion batteries) [110,111]. Hybridization provides greater benefits during transient operations: numeric simulations demonstrated as the replacement of a traditional ICE crane leads to CO_2 emissions reduction up to 70 % [112]; moreover, the use of batteries and ultracapacitors in cranes showed higher efficiencies respect to the commonly used ICE, together with the possibility to operate disconnected from the grid [113].

Nonetheless, hybridization showed the most interesting results when hydrogen-fuelled FC are coupled with electric storage systems, because of the aforementioned FC advantages over ICE. To date, only few studies are focused implementing hybrid technologies for both cargo handling equipment and vehicles operating in port areas (Table 1). Among them, hybrid hydrogen yard tractors and a mobile hydrogen refuelling station are under test within the Port of Valencia [114]. A hydrogen-powered tractor (equipped with four 350 bar hydrogen fuel tanks, containing a total of 14.4 kg of hydrogen) is under testing in the Port of Rotterdam [115]. The convenience of replacing ICE was also assessed by comparing the total carbon emissions of four type of yard tractors at the Port of Kaohsiung: diesel-fuelled ICE, LNG-fuelled ICE, hydrogen-fuelled FC, and a fully electric one. As a result, the use of hydrogen-fuelled tractors allows to reduce GHG emissions about 69 % with respect to the diesel-fuelled ones [116]. Similar approaches were also applied to intermodal means of transportation by evaluating the impact of hybrid powertrains for railways based on hydrogen-fuelled FC [117], while other studies addressed to FC only, in particular to the comparison of different FC-based powertrains for locomotives, coupling together solid oxide FC, Proton Exchange Membrane FC and gas turbines fuelled by NH_3, NG and/or hydrogen [118,119]. Finally, it is worth to notice as FC constitute a promising solution for the heavy-duty transportation, which develops along repetitive and predictable routes, thus requiring less spread infrastructural investments (e.g. refuelling station) and limiting the capital expenditure [120]. In this framework, FC-powered heavy-good-vehicles could achieve peak tank-to-wheel efficiencies up to 50 %. Advancements in hydrogen storage and energy conversion performances could lead to results comparable with targets set to be reached in between 2025 and 2035 in terms of gravimetric and volumetric energy densities in comparison with conventional fuels [121].

2.4. *Power generation and storage from renewable energy sources*

To date, several types of RES were developed and for some of them, their full potential is still unexplored: in this scenario, ports might constitute hubs for developing new solutions. For example, the possibility to use tidal-based energy production in the ports of Aviles [122] and Ribadeo [123] was explored, as has the possibility of producing energy from waves [124,125] in the Port of Valencia [126]. Conversely, photovoltaic plant installation in IPA is often addressed in literature and several projects already include high photovoltaic power capacity plants (especially on building rooftops) [127]. Photovoltaic technologies represent the most exploited RES, followed by wind farms [14], which are usually installed offshore [128]. To date, several offshore wind farms are present in IPA both in the USA (ports of NYNJ, Long Beach, San Diego, San Francisco) and within the EU (ports of Hamburg, Zeebrugge, Rotterdam, Amsterdam, Antwerp) [99,129]. To date, wind farm spreading is main limited by the availability of areas dedicated to their installation or by the legislative framework in which IPA are located. In this scenario, constituting shared-energy agreements for green energy supply could help in spreading such technology, as investigated in the context of the EU E-harbor project [130], and implemented by the Port of Rotterdam [131]. Issues regarding the intermittent and non-predictable nature of RES could be partially overcome with the installation of energy storage systems, and hydrogen produced via electrolysis seems to be here a valid option [7]. For example, the Port of Rotterdam is planning to produce hydrogen from RES to be used for fuelling FC-powered yard tractor fleet within the IPA [132]. Similarly, the Groningen Seaports host several pilot plants for production, storage and use of green hydrogen, forming a remarkable hydrogen-based clustered with the surrounding industries [133].

Although the management of RES, electric storage systems, hydrogen production and storage, and their effective environmental impact assessment are complex issues to be addressed simultaneously, different methodologies for facing such issues were proposed [98,134]. Among them, Misra et al. [98] modelled the port energy systems to find the optimal operational strategies for matching port energy demand including wind, solar, and biomass energy sources, Manolis et al. [134] analysed the effects of a dedicated response strategy of voltage enhancement in port energy distribution networks via multi-agent systems, and several studies proposed the integration of RES power systems and the port grid in smart grids [13,52,135,136]. Wang et al. [136] addressed the optimisation of microgrid design and operation in ports, by considering the exploitation of multiple RES distributed within the microgrids, Ahamad et al. [52] showed that RES-based smart grids could reduce the port environmental impact and 75 % RES share could be achieved using existing power and energy storage technologies in the Port of Copenhagen. Finally, Prousalidis et al. [135] proposed the creation of a smart energy system in port efficiently matching RES production with OPS power demand.

2.5. *Import and export of energy*

Several countries are heavily dependent on the shipment of imported fossil fuels, especially in the absence of pipelines or rail connections with exporting countries. Nowadays, the 31 % of shipping trade in weight consists of fossil fuels, and ship-transported oil and coal represent respectively the 16 % and the 11 % of the global shipping trade (Fig. 4). The exchange of LNG represents the 4 % of the whole, with a growing trend: with respect 2020, the exchanged volume of LNG showed an increase by 6 %, reaching the total value of 380 million of tons [137].

In the energy market, production sites are generally located in proximity of the extraction and processing sites, whereas consumption is usually spread in different locations. Thus, global shipping and ports become fundamental, acting as energy hub in receiving, producing, and/or supplying energy to both urban and industrial districts. In addition, industries settled in IPA can directly benefit from an immediate access to feedstocks, thanks to the reduced transportation costs and to the easier access to multiple suppliers [138].

In a well-established hydrogen economy, ports could play an even more fundamental role within the energy trade [5,6]. Countries with exceeding energy production via RES could sell their surplus in form of hydrogen: the Australian Government already proposed the development of hydrogen hubs in proximity of port facilities to promote

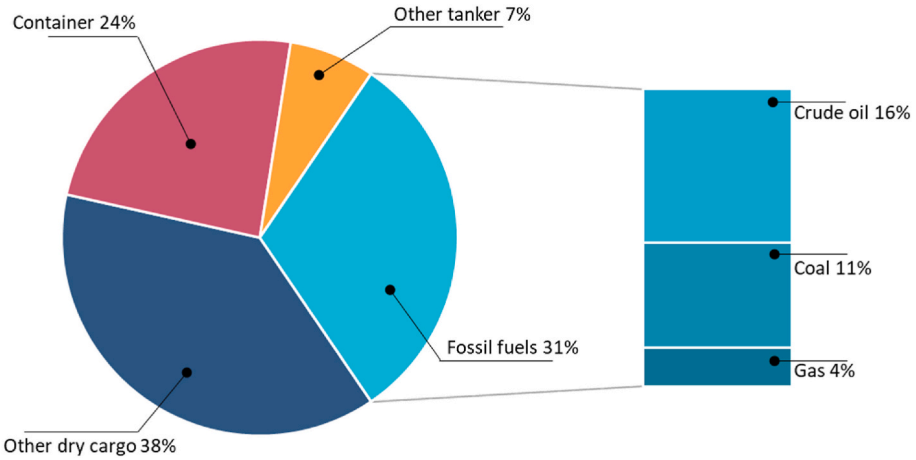

Fig. 4. Breakdown of global shipping trade in weight. In 2020 fossil fuels occupy about one third of the whole shipping trade. Among them, natural gas and liquified natural gas represent the 4 % of the total exchanges, showing a growing trend [1]. Other fuels, such as propane or ethanol are not included due to their negligible weight.

hydrogen export and identified the most suitable thirty national ports for their establishment [139]. Also the Government of Chile presented its own hydrogen strategy, making seaports play a central role in handling hydrogen export [140]. In Canada, ports were imagined forming a backbone for the export of hydrogen produced in the Central Canada region. Canadian hydrogen strategy [141] also pointed out that ports could benefit from using hydrogen as fuel for heavy-duty vehicles operating in port areas, fulfilling the fuel demand needed in a single location to drive scale- and cost-effective deployment of hydrogen systems. The use of hydrogen to power vessels from on-shore and transport-refrigeration units staged at ports was also considered [141]. In the Netherlands, the development of hydrogen-based infrastructures mixed within industrial clusters and port areas are becoming a key pre-requisite for further sustainability improvements due to the closed connections between ports and industries, as well as to the development of pilot-demo projects focused for achieving a climate-neutral industrial sector by 2050 [142]. In addition, the International Renewable Energy Agency (IRENA) estimated that about 614 Mt_{H2}/year will be necessary to limit the 1.5 °C increase of global temperature by 2050 and that about the 25 % of the total hydrogen demand (153 Mt hydrogen per year) is going to be traded in 2050. In Fig. 5, it is summarized as the 55 % of the globally traded hydrogen is estimated to be transported via pipelines, the 45 % is estimated to be transported via ship, 40 % as NH_3 and 5 % as LH_2. Fig. 5 also focuses on the use of NH_3 transported via ship: green NH_3 is expected to be transported and largely used as fertilizer (267 Mt/y) and marine fuel (197 Mt/y), the rest as hydrogen carrier (127 Mt/y) or for other use (97 Mt/y). Considering the NH_3 traded by ship and the NH_3 domestically consumed (168 Mt/y), in 2050 the total green NH_3 production will reach the amount of 566 Mt/y, about three times the current rate of worldwide NH_3 production [97].

The presence of ships dedicated to hydrogen trading was extensively investigated, starting from the production of different hydrogen carriers from RES [143]. In this framework, Hank et al. propose the assessment of techno-economic efficiency of imported energy carriers based on renewable electricity [144,145]. Bargiacchi et al. [146] compared four synthetic fuel production chains starting from water electrolysis: methane synthesis (via Sabatier process), methanol synthesis (by CO_2 hydrogenation), NH_3 production (via the Haber-Bosch process) and urea synthesis (with Stamicarbon CO_2 stripping). They concluded that methane production is the most efficient process, although NH_3 production (second in efficiency) has the potential to be carbon-neutral if powered by RES. Other studies evaluated the global potential benefit in economic and environmental terms, such as the feasibility of exporting hydrogen with low carbon impact from for the Western Canada to the Eastern Canada, the USA, the Asia-Pacific, and Europe [147], or compared via life cycle assessment different scenarios for Germany future demand combined with its domestic production [148]. Analogously, Eckl et al. [149] proposed a techno-economic comparison of two hydrogen supply options, the onsite production in Germany and the import from Portugal, while Hjeij et al. [150] reviewed the economic

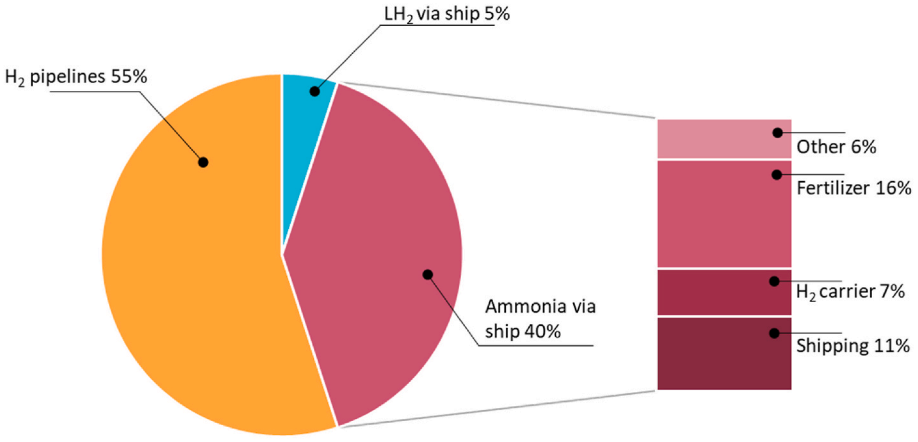

Fig. 5. Foreseen breakdown of global hydrogen trade in 2050. Prevision of future global hydrogen trade volume in 2050. Data are referred to an optimistic technology scenario in 2050 defined by the International Renewable Energy Agency (IRENA) [97].

opportunities offered by the development of hydrogen technologies for natural gas-exporting countries and proposed five indicators for comparing the potential hydrogen export of different countries. By focusing on hydrogen import on the pollutant emissions in Japan, it was pointed out as hydrogen could have only a marginal role in the decarbonizing power generation, while it could be a cost-efficient way for producing electricity and heat for commercial and residential buildings, providing cycling and ramping capabilities for power system [151].

2.6. Interplay with industries and port cities

The ease of access to consumer goods, raw materials, and job opportunities had always promoted cities growth around ports. However, the benefits to the industrial and technological development are nowadays bounded to life quality reduction, due to pollutants emission from IPA [41]. Though, fossil fuels replacement can be particularly hard when they also constitute a feedstock for production chains (in the so-called hard-to-abate sectors). Several decarbonization-oriented approaches have been proposed and/or adopted by port authorities. Among them, microgrids development for integrating both ports and cities into a distributed network of power sources and loads has been largely tested [152,153], thanks to microgrid flexibility in adapting to the wide range of loads characterizing vehicles and infrastructures [152]. Mousavi et al. [154] proposed a general control strategy consisting of active and reactive power controllers and a voltage/current quality-improvement block, while Yigit et al. [155] developed an energy management approach and algorithm specifically designed for ships using mixed energy sources. Moreover, lot of work has still to be done for optimizing the overall efficiency, because microgrid complexity grows exponentially with the number of the nodes composing it [156–158], and issues related to non-homogeneous daily energy distribution [13,88], or an effective creation of hybrid renewable energy systems [159] still needs to be overcome.

Apart from local conditions, more generalized observations can be addressed to the hydrogen- or hydrogen-carriers-based decarbonization strategies of different hard-to-abate industrial sectors, such as the iron and steel industries, refineries, and the chemical industry. In this context, considerations involving electrification and the use of RES and biofuels are not analysed because they are beyond the scope of this work. RES-based hydrogen production was recently investigated for decarbonizing the metallurgic and the chemical industries. Concerning metallurgy, examples were found involving iron [160], steel [161] and aluminium [162] production cycles: Ren et al. [160] estimated a 23 %–25 % increase of hydrogen-based direct reduction share by 2050 in iron and steel production in China. Moreover, Muslemani et al. [161] identified a set of potential demand-side and supply-side policy mechanisms to support green steel production and to resolve various carbon accounting and assurance issues, which otherwise had the potential to lead to perverse outcomes and opportunities for greenwashing. Finally, Sgouridis et al. [162] investigated the economic and environmental impact of coupling RES with hydrogen storage to decarbonize the aluminium-related industrial sector and proposed a 100 % RES configuration for the smelter powered by: 5.4 GW single-axis tracking photovoltaics, 0.2 GW wind turbines, 18 GWh of battery storage and 47 GWh of hydrogen storage. Within chemical industry, the main measures were found in decarbonization of NH_3 production [163] and general emission preventions [164]. In particular, the feasibility to use hydrogen as an energy vector for petroleum refineries and NH_3 synthesis in India was found to levelized hydrogen cost from 2.2 to 8.64 US$/kg [163]. By evaluating the possibilities for decarbonizing the energy-intensive chemical industries, the green hydrogen resulted a good option to be used, mixed to biomass and/or CO_2, for hydrocarbons production (as methanol and methane) [164]. Concerning the glass production, hydrogen combustion was proven to be a valuable support to be used whenever the equipment cannot be electrified [165], while it was estimated that the copper industry could benefit of reducing CO_2 abatement costs from 201 €/t $CO_{2,eq}$ to 54 €/t $CO_{2,eq}$ if green hydrogen would be introduced to power supply the industrial processes [166]. Improvements in decarbonizing refineries could be made by substituting grey hydrogen with the green one [163,167,168]: for example, Wang et al. [167] proposed a mathematical model for finding optimal design and operation point of an energy storage system with multiple energy carriers for matching the intermittent RES and the fluctuating demands of hydrogen and oxygen, while Nurdiawati et al. [168] proposed a series of hybrid approaches, considering simultaneously the use of biofuels, green hydrogen, and carbon capture and storage technologies for decarbonizing Swedish refineries.

3. Analysis of hydrogen-related projects in worldwide ports

In the last years, an increasing number of worldwide-spread projects addressing the development of infrastructures dedicated to hydrogen production, storage, distribution, and use for ports decarbonization is reported. An analysis on how international ports are facing the decarbonization issues considering the use of hydrogen was carried out on the 60 largest container ports [169]. Smaller ports involved in the development of hydrogen projects, as reported in Refs. [170,171], were also included in the survey. Information, in English, freely available on the web was collected in a database, available as Supplementary Material in the online version of this paper. Before 2014, to the authors' knowledge, only small projects involving hydrogen use in ports were found and were not considered for this analysis. In the Supplementary Material, projects are catalogued according to project name, funding involved, project country, start and end date, progress of the project, proposed hydrogen production, proposed hydrogen use and project partners. Data about the proposed hydrogen technologies involved and information about actions carried out by ports towards decarbonization are also included. Ports for which the authors did not find sufficient information regarding the development of hydrogen projects are not mentioned in the analysis.

As a first outcome, most of the projects collected are still to be concluded (84 %). At the time at writing (November 2022), 74 projects were identified being started or under development within 36 ports worldwide spread. According to the information available to the authors, 80 % of projects are in Europe. In fact, the EU is providing ample information and emphasis on the use of hydrogen as a sustainable feedstock, fuel and/or energy carrier to reduce carbon emissions, granting several initiatives and funding programmes, such as Fit-for-55, REPowerEU and Horizon Europe [8,172]. As shown in Fig. 6, in 12 projects, distributed over 10 ports, the hydrogen production and/or use is already in place. In particular, a hydrogen refuelling station is operating since 2018 in Delfzijl for powering two hydrogen buses [173], a terminal tractor is operating in the ports of Rotterdam [115] and Valencia [114]. In addition, a hydrogen-fuelled passenger ferry, a dual fuel (hydrogen and diesel) tug and a hydrogen refuelling station to be used both for heavy-duty vehicles and ships were developed in the Port of Antwerp-Bruges [103,174,175]. A pilot plant was built at the Port of Jerome for the production of low carbon hydrogen via steam methane reforming provided with a carbon capture system [176]. A push boat was developed and tested in the Port of Hamburg [177], a testing platform was built in the Port of Long Beach to compare performances of different hydrogen-powered trucks dedicated to inter-port logistics [178], and a hydrogen refuelling station was built in the Port of Auckland to supply buses serving the inland [179]. Finally, in the context of HESC project a LH_2 loading and unloading infrastructures were built for shipping hydrogen (produced by coal gasification and carbon capture and storage) from the Port of Hastings to the Port of Kobe [180].

As shown in Fig. 6, most of the projects are focused in using hydrogen for powering the existing heavy-duty vehicles which are operating internally and externally the ports areas. Among different types of vehicles, most of the ports proposed the use of hydrogen for trucks and buses, such as in the Groningen Seaports, the Port of Amsterdam and the Port of Long Beach (Los Angeles). Instead, Port of Rotterdam and Port of

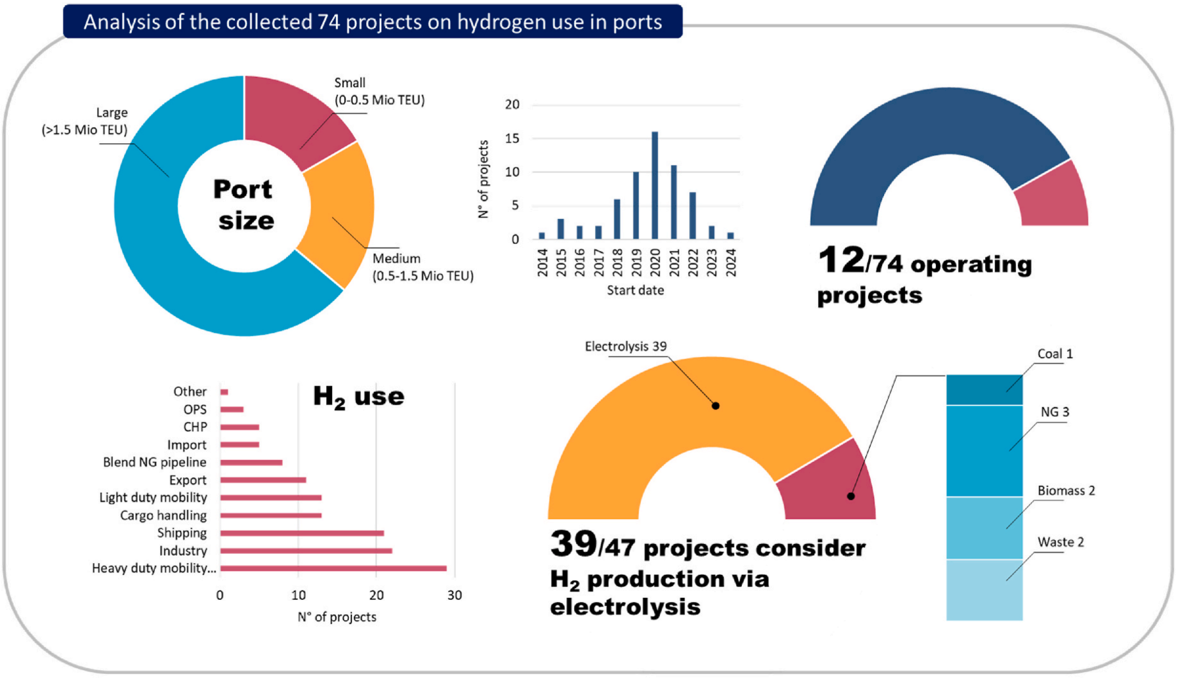

Fig. 6. Subdivision of considered hydrogen projects by hydrogen production and use and port size. The main results of the review process are here displayed, including projects developed, under development or planned. Information addressing the use of hydrogen in IPA are additionally included.

Valencia (as well as in other 11 ports) proposed the use of hydrogen for fuelling vehicles used for handling cargo in ports, e.g. yard tractors and reach stackers. More than 20 projects are addressing the use of hydrogen for industry decarbonization and/or as alternative fuel for shipping. Industrial hydrogen applications are proposed for example in the IPA of Delfzijl, Rotterdam and Hamburg, while the bunkering of hydrogen or hydrogen-based fuels are considered in the ports of Antwerp-Bruges, Duisburg and Vigo.

The examples below illustrate how hydrogen is being implemented in emission-reducing strategies in IPA.

The **Port of Rotterdam** is actively participating in several programmes with the aim of becoming the hydrogen hub for all of the Northwest Europe with an estimated annual hydrogen throughput of 20 Mt [132,181]. Here, nine hydrogen-based projects are currently under development, addressing both to blue (e.g., H-vision [132]) and green (e.g., CurtHyl [182]) hydrogen productions, as well as to importing it from the Portuguese Port of Sines (Green Flamingo [183]). In cooperation with refineries belonging to both Shell and British Petroleum, the port authority is also investigating the feasibility of installation of respectively 200 MW and 250 MW electrolyser capacities for green hydrogen production. By hosting such electrolysers, the Port of Rotterdam can become a hydrogen hub and a point of reference for decarbonizing the surrounding heavy industrialized area [181]. Approximately 13 M€ private funds are directed to the development of a supplementary 26 MW electrolyser by 2025 for hydrogen supply to ships, light-duty vehicles and heating systems (H2GO [184]). Important information about hydrogen use for cargo-handling equipment and heavy-duty mobility in ports, can be derived from the expertise developed within the ports of Valencia and Long Beach (Los Angeles) [114, 185,186]. The **Port of Valencia** is developing a yard tractor and a reach stacker both fuelled by hydrogen and powered by FC technologies, together with a mobile hydrogen refuelling station, specifically designed in the project to refuel these two vehicles (H2Ports [114], total investment of 4 million €, financed by the Clean Hydrogen Joint Undertaking). The reach stacker is under development at Hyster-Yale Group, Inc., while the yard tractor involves the installation of a FC powertrain in an electric tractor to extend its operative range. The mobile refuelling station is planned to encompass a two-stage water-cooled piston hydrogen compressor, two groups of hydrogen storage cylinders (300 and 450 bar) and a dispenser at 350 bar for heavy-duty vehicles [114]. Hydrogen will be produced by means of the electrolysers recently installed in the north quay of the port [185]. The **Port of Long Beach** is currently testing the use of ten hydrogen-powered heavy-duty FC class-8 trucks (developed by Toyota and Kenworth, with a 79 M€ project financed for 40 M€ by the California Air Resources Board grant) [186]. Hydrogen is going to be supplied by an internal refuelling station coupled with a hydrogen production plant consisting in a tri-generation system (by FuelCell Energy), able to produce simultaneously 1.2 t_{H2}/day, heat and 2.35 MW of electricity with potential zero carbon emission when fed by biogas [170,187]. The **Port of Hamburg** in collaboration with the ArcelorMittal facility and thanks to the funding from the German Federal Government (55 M€) has planned: the installation of a hydrogen fuelled pilot plant for the direct reduction of iron ore (H2first [187,188]), the upgrade of the existing direct reduction plant (H2Ready [187,188]), and the replacement of the NG currently used with green hydrogen within the 2030 [189,190]. In addition, it is also involved in promoting the use of hydrogen for decarbonizing shipping, cargo handling vehicles, heavy-duty mobility, and buildings heating systems, aiming to introduce hydrogen-fuelled straddle carriers, trucks, tractor trucks, forklifts, masted container handlers, reach stackers, and shunting locomotives (H2LOAD [191]). In parallel, it has started investigating the possibility to build hydrogen refuelling stations dedicated to hydrogen-based ships vehicles operating within the port (HyPA [192]). Finally, the port is involved in projects specifically focused on the realization of ships powered by hydrogen (H2PushBoat [177] and H2HADAG [193,194]). Up to date, the aforementioned projects are still under development and, up to the authors' knowledge, no operative equipment has been reported yet. Additional projects are under development in other Dutch ports: the **Port of Amsterdam**, the **Groningen Seaports** and the **Port of Den Helder** are cooperating with the aims of developing both a hydrogen pipeline connecting Amsterdam and Ijmuiden, and a blue hydrogen production site in the Port of Den Helder and with the aim of installing of a 100 MW electrolyser for green hydrogen production in the industrial area of Eemshaven for decarbonizing hard-to-abate industries (Hydroports [195]). The Port of Den Helder and the Groningen Seaports, together with the Port of Harlingen, are further engaged in developing a FC-based generators for OPS (Green Shipping Wadden [196]). The Groningen Seaports are also participating to other programmes dedicated to hydrogen economy promotion: the port authority is involved in reaching 3 ÷ 4 GW of wind power production for hydrogen generation by 2030 (with an upscale up to 10 GW before 2040), with a final goal of a yearly production of 750, 000 tons of green hydrogen by 2040 for industrial users (NorthH2 [197]). Finally, they are also responsible for the development of a pipeline infrastructure for green hydrogen distribution among different industrial users in the Chemie Park in Delfzjil (HEAVENN [198,199], financed with 88 M€) and for the realization of a green hydrogen production plant via a 60 MW electrolyser system (currently under design), which will be divided in two facilities (Djewels 1, 20 MW, funded with 16 M€) and Djewels 2 (40 MW) [200]. In addition, the Port of Amsterdam is going to build and operate a 20 m vessel powered by a hybrid hydrogen-fuelled-FC/battery propulsion system with the scope of demonstrating the technical and economic feasibility of hydrogen bunkering and propulsion systems (H2SHIPS, [201]; investment cost of 6.3 M€, 3.5 M€ of them funded by the EU).

Summarizing, most projects are being developed in medium and large European ports (i.e., handling more than 0.5 TEU/y), where both public and private are directed at developing technologies involving green hydrogen and promoting their integration with existing industrial networks. In fact, especially in Northern Europe, IPA benefit from a well-established industrial network that allows easier hydrogen distribution (e.g., via existing pipelines) and distributed hydrogen production via electrolysis thanks to the wide availability of RES plants, such as offshore wind in Hamburg, Rotterdam and Amsterdam. Hydrogen is proposed here mainly for the decarbonization of heavy industry, which requires less upfront expenditure to adapt infrastructure for its use and which must use green fuels and feedstock due to the difficult electrification of processes. The creation of an initial supply and demand for green hydrogen in the hard-to-abate sectors can then drive the increasing use of hydrogen also in the mobility and shipping.

4. Concluding remarks and future trends

This study proposes a comprehensive review of decarbonization strategies for industrial port areas (IPA), with a particular focus on the role that hydrogen could play when used as: fuel (for ships, port vehicles, equipment, and inter-port logistic vehicles), energy carrier (for onshore power supply (OPS) and other port demands), and as feedstock for industries.

IPA decarbonization is nowadays a topic of interest, as demonstrated not only by the large amount studies available in literature, but also by the inclusion of priority actions in national and international strategies, and by the initiatives and projects currently ongoing in IPA worldwide. Increasing penetration of RES could have a great impact in reducing emissions, mainly when coupled with an overall increase of energy efficiency. However, a complete IPA decarbonization is not achievable by barely electrifying industrial processes and equipment, as some applications require consistent techno-economic efforts, which can still be sometimes out of reach in the short or medium term. Moreover, being able to match at best RES demand and supply, could be realized only in presence of large energy storage systems. In this context, hydrogen and hydrogen-carriers could play a key role in storing the exceeding energy produced from RES, which would be stored or distributed to be later used as renewable energy carrier. Ports could here not only promote a new hydrogen economy, but also create new energy markets. However, there are still several technical and economic barriers to be overcome for a successful deployment of decarbonization strategies. In particular.

- **OPS** could effectively impact on reducing GHG emissions in ports, as 70–100 % of emissions in IPA are due to ship traffic, but the installation of new infrastructures is hampered by port grids capacity, high capital expenditures, operating expenses, and by the different power supply specifications between port grids and vessels. Although operating expenses remain strictly related to port locations, adopting a common standard would allow to overcome technical barriers, while capital expenditure and green hydrogen costs are expected to decrease if a broader diffusion of hydrogen-based technologies will also be applied to OPS infrastructures. In parallel to promote infrastructural expansion of port grid capacity for supporting OPS, green-hydrogen-powered-FC revealed to be a good option for ports with limited port grid capacity. To date, FC costs limit their use to stationary applications, especially for CHP units providing heat and power to ships or port users.
- **Port equipment, cargo handling vehicles and inter-port logistic vehicles** are currently responsible for the 15 % of the total pollutants and GHG emission in IPA. Hybridization of diesel-fuelled ICE powertrains could represent a good option for reducing emissions, together with the use of alternative fuels or by using fully electrified vehicles. To date, hydrogen-powered FC represents one the main option ensuring zero local emissions and allowing comparable performances with respect to the conventional existing technologies. High costs, and the lack of both a hydrogen-dedicated infrastructure and legislative standards are limiting the operation of hydrogen vehicles within IPA. Given to their specifications in terms of power required and autonomy of operation, cranes, yard tractors and forklifts would be suitable for a quick conversion to hydrogen-based technologies. However, only a few prototypes have been developed and the technology still has a low TRL. To date, for cranes and locomotives, electrification is currently the winning strategy if when they could be directly connected to the power grid, while for vehicles which could not be connected to the grid, there are no alternatives to ICE-batteries hybridization. In this case, the use of alternative fuels for the ICE can be investigated.
- **Shipping** represents one of the most significant sources of pollution and GHG in port areas together with industries. Building infrastructures for bunkering alternative fuels is an important step for a progressive transition towards a sustainable shipping. To date, LNG, biodiesel and ammonia are the most promising options due to their reduced carbon impact with respect to marine diesel oil and heavy fuel oil, and to their easy deployment in conventional ICE. In the medium-term, hydrogen-fuelled FC could be a good option for guaranteeing zero-emission shipping: LH_2 seems to be the most efficient solution for larger ships, while cH_2 could be stored for small- and medium-sized ones. Besides the techno-economic limitations of hydrogen storage and use the biggest obstacles are the lack of regulations for the use of hydrogen as a fuel for ship propulsion and the lack of standards for bunkering cH_2 and LH_2.
- **Import and export of green energy carriers, fuels and feedstocks** could become crucial in the next years, if ports are going to evolve into hubs for the import/export energy vectors. In the medium term, ammonia seems to be the most advantageous hydrogen carrier due to well-developed industrial and logistical infrastructure for its handling and good efficiency for its production and conversion back into hydrogen. However, in the long term, improvements in cryogenic technologies for the liquefaction, storage and distribution of LH_2 could favour it, due to the high overall efficiency from its production to its use. In this framework, safety concerns about using and handling LH_2 in ports, as well as efficiency of its loading and unloading, and possibilities of cold recovery, still need to be fully investigated.
- Consequently, **industries** operating in IPA might have an easy access to green energies imported or produced by ports, and feedstock and materials produced via industrial processes characterized by low carbon impact could form new and sustainable trading routes. Ports could also promote **port cities** decarbonization by creating a network of green, microgrid-based, distribution systems. An efficient

introduction of hydrogen into industrial processes and infrastructures should be at first focused to the replacement of the existing hydrogen with green one. Then, hydrogen-based solutions should be promoted for powering industrial equipment and for heating generation, by exploiting the better performances of hydrogen with respect electrification when dealing with equipment which is currently operating with big fossil fuel consumption. Finally, building shared infrastructures between ports, cities and industries could help in increasing the efficiency of RES and use of multi-energy sources, considering simultaneously fuel, electrical and thermal energy flows. In this framework, the investigation and development of advanced computational tools dedicated to optimizing the energy flows management in terms of cost-effectiveness and carbon footprint reduction would be needed.

- With respect to **power production from RES**, and due to their strategic position, ports could exploit different available RES, such as solar, wind, waves and tidal energy sources. Nowadays photovoltaic systems and wind turbines are mostly deployed in IPA. Whenever RES production exceeds the energy demand, water electrolysis could represent a good solution for green hydrogen production. To date, the lack of green hydrogen demand and the high cost of electrolysers limit their installation in IPA. To promote diffusion of RES-based green-hydrogen production, the optimal integration (thus including heat/cold recovery strategies) of local hydrogen production systems via electrolysis by using the existing energy systems should be investigated, together with the possibility of supplying hydrogen to industries, vehicles and ships.

As a final remark, financial and economic incentives are still required to promote the spreading of the hydrogen-based technologies. Funding and financing research and development is also necessary to improve the ongoing technological scaling up and the process overall efficiency. The development and installation of dedicated infrastructures in port areas would also require a new planning of port buildings and equipment distribution, and this might slow down the innovation process in bigger ports. However, and under the proper financial support, small ports could be favoured and play act as facilitators of such a transition in the short-medium term, due to their greater flexibility in infrastructural planning and management. Likewise, ports located in remote and island areas could reduce operation costs and create new markets by exploiting RES and/or importing green hydrogen carriers. In the medium-long term, a full penetration of hydrogen technologies in the IPA framework could be achieved with the cooperation of the industry, port and shipping sectors, subject to progressively stricter environmental standards required globally.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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References

[1] United Nations Conference on Trade and Development (UNCTAD). Review of maritime transport. 2016.
[2] United Nations (UN). The Ocean conference. 2017. New York.
[3] Ahamad NBB, Guerrero JM, Su CL, Vasquez JC, Zhaoxia X. Microgrids technologies in future seaports. In: Proc - 2018 IEEE int conf environ electr eng 2018 IEEE ind commer power syst eur EEEIC/I CPS eur; 2018 2018. p. 1–6. https://doi.org/10.1109/EEEIC.2018.8494428.
[4] Rødseth KL, Schøyen H, Wangsness PB. Decomposing growth in Norwegian seaport container throughput and associated air pollution. Transport Res Transport Environ 2020;85:102391. https://doi.org/10.1016/j.trd.2020.102391.
[5] Ports: green gateways to Europe DNV n.d. https://www.dnv.com/Publications/ports-green-gateways-to-europe-179372 (accessed November 8, 2022).
[6] Rodrigue J-P. Ports and energy. In: Routledge, editor. Port econ. Manag. Policy; 2022.
[7] Lind M, Pettersson S, Karlsson J, Steijaert B, Hermansson P, Haraldson S, et al. Sustainable Ports as Energy Hubs. n.d. https://doi.org/10.13140/RG.2.2.15434.70084.
[8] RepowerEU nd. https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131. [Accessed 10 November 2022].
[9] Hydrogen Council. Path to hydrogen competitiveness: a cost perspective 2020.
[10] Zheng Y, Zhao J, Shao G. Port city sustainability: a review of its research trends. Sustain Times 2020;12:1–17. https://doi.org/10.3390/su12208355.
[11] Lim S, Pettit S, Abouarghoub W, Beresford A. Port sustainability and performance: a systematic literature review. Transport Res Transport Environ 2019;72:47–64. https://doi.org/10.1016/j.trd.2019.04.009.
[12] Alamoush AS, Ballini F, Ölçer AI. Ports' technical and operational measures to reduce greenhouse gas emission and improve energy efficiency: a review. Mar Pollut Bull 2020;160. https://doi.org/10.1016/J.MARPOLBUL.2020.111508.
[13] Iris Ç, Lam JSL. A review of energy efficiency in ports: operational strategies, technologies and energy management systems. Renew Sustain Energy Rev 2019;112:170–82. https://doi.org/10.1016/j.rser.2019.04.069.
[14] Sifakis N, Tsoutsos T. Planning zero-emissions ports through the nearly zero energy port concept. J Clean Prod 2021;286:125448. https://doi.org/10.1016/j.jclepro.2020.125448.
[15] Ortiz-Imedio R, Caglayan DG, Ortiz A, Heinrichs H, Robinius M, Stolten D, et al. Power-to-Ships: future electricity and hydrogen demands for shipping on the Atlantic coast of Europe in 2050. Energy 2021;228:120660. https://doi.org/10.1016/j.energy.2021.120660.
[16] Kinnon M, Mac, Razeghi G, Samuelsen S. The role of fuel cells in port microgrids to support sustainable goods movement. Renew Sustain Energy Rev 2021;147:111226. https://doi.org/10.1016/j.rser.2021.111226.
[17] European Commission. Horizon 2020 work programme 2016–2017.
[18] Cigolotti V, Genovese M, Fragiacomo P. Comprehensive review on fuel cell technology for stationary applications as sustainable and efficient polygeneration energy systems. Energies 2021;14:4963. https://doi.org/10.3390/EN14164963. 2021;14:4963.
[19] Bianchi FR, Bosio B, José F, Fernández H. Operating principles, performance and technology readiness level of reversible solid oxide cells. Sustain Times 2021;13:4777. https://doi.org/10.3390/SU13094777. 2021;13:4777.
[20] Dall'Armi C, Micheli D, Taccani R. Comparison of different plant layouts and fuel storage solutions for fuel cells utilization on a small ferry. Int J Hydrogen Energy 2021;46:13878–97. https://doi.org/10.1016/J.IJHYDENE.2021.02.138.
[21] Dall'Armi C, Pivetta D, Taccani R. Hybrid PEM fuel cell power plants fuelled by hydrogen for improving sustainability in shipping: state of the art and review on active projects. Energies 2023;16:2022. https://doi.org/10.3390/EN16042022/S1.
[22] van Veldhuizen B, van Biert L, Aravind PV, Visser K. Solid oxide fuel cells for marine applications. Int J Energy Res 2023;2023:1–35. https://doi.org/10.1155/2023/5163448.
[23] Steele L.M., Myers C. Hydrogen fuel cell applications in ports. H2@Ports Int Work 2019. n.d. https://www.energy.gov/sites/prod/files/2019/10/f68/fcto-h2-at-ports-workshop-2019-viii3-steele.pdf (accessed October 26, 2023).
[24] Zero-emission cargo-handling equipment feasibility assessment AECOM 2019.
[25] Pivetta D, Volpato G, Carraro G, Dall'Armi C, Da Lio L, Lazzaretto A, et al. Optimal decarbonisation strategies for an industrial port area by using hydrogen as energy carrier. Int J Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2023.07.008.
[26] Reksten AH, Thomassen MS, Møller-Holst S, Sundseth K. Projecting the future cost of PEM and alkaline water electrolysers; a CAPEX model including electrolyser plant size and technology development. Int J Hydrogen Energy 2022;47:38106–13. https://doi.org/10.1016/J.IJHYDENE.2022.08.306.
[27] Glenk G, Reichelstein S. Economics of converting renewable power to hydrogen. Nat Energy 2019;4:216–22. https://doi.org/10.1038/s41560-019-0326-1.
[28] Trattner A, Höglinger M, Macherhammer MG, Sartory M. Renewable hydrogen: modular concepts from production over storage to the consumer. Chem Ing Tech 2021;93:706–16. https://doi.org/10.1002/CITE.202000197.
[29] International Energy Agency (IEA). The Future of Hydrogen: seizing today's opportunities. Propos Doc Japanese Pres G20; 2019.
[30] Koleva M, Melaina M. Hydrogen fueling stations cost. DOE Hydrogen Program Record; 2020.
[31] Haskel | High-Pressure Technology Solutions n.d. https://www.haskel.com/en-it/(accessed July 24, 2023).

[32] 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;10:1222. https://doi.org/10.3390/JMSE10091222. Page 1222 2022;10.

[33] Klebanoff LE, Pratt JW, Madsen RT, Caughlan SAM, Leach TS, Appelgate TB, et al. Feasibility of the zero-V: a zero-emission, hydrogen fuel-cell, coastal research vessel leonard. Sandia Natl Lab; 2018.

[34] International Maritime Organization (IMO). Fourth greenhouse gas study. 2020.

[35] Merk O. Shipping emissions in ports. Int Transp Forum's Discuss Pap 2014;20:37.

[36] Power Technology Research (PTR). Onshore Power Supply Gaining Popularity in European Ports n.d12; July 2022. https://powertechresearch.com/onshore-power-supply-gaining-popularity-in-european-ports/(accessed.

[37] World Port Sustainability Program (WPSP). Onshore Power Supply n.d. https://sustainableworldports.org/ops/(accessed November 8, 2022).

[38] Qi J, Wang S, Peng C. Shore power management for maritime transportation: status and perspectives. Marit Transp Res 2020;1:100004. https://doi.org/10.1016/J.MARTRA.2020.100004.

[39] Zis TPV. Prospects of cold ironing as an emissions reduction option. Transport Res Part A Policy Pract 2019;119:82–95. https://doi.org/10.1016/J.TRA.2018.11.003.

[40] Stolz B, Held M, Georges G, Boulouchos K. The CO2 reduction potential of shore-side electricity in Europe. Appl Energy 2021;285. https://doi.org/10.1016/j.apenergy.2020.116425.

[41] Chatzinikolaou SD, Oikonomou SD, Ventikos NP. Health externalities of ship air pollution at port – Piraeus port case study. Transport Res Transport Environ 2015;40:155–65. https://doi.org/10.1016/J.TRD.2015.08.010.

[42] Spengler T, Tovar B. Potential of cold-ironing for the reduction of externalities from in-port shipping emissions: the state-owned Spanish port system case. J Environ Manag 2021;279:111807. https://doi.org/10.1016/J.JENVMAN.2020.111807.

[43] Jayasinghe SG, Al-Falahi M, Enshaei H, Fernando N, Tashakori A. Floating power platforms for mobile cold-ironing. IEEE 2nd Annu South Power Electron Conf SPEC 2016 2016; 2016. https://doi.org/10.1109/SPEC.2016.7846221.

[44] Pratt JW, Harris AP. Vessel cold-ironing using a barge mounted PEM fuel cell: project scoping and feasibility. 2013.

[45] Williamsson J, Costa N, Santén V, Rogerson S. Barriers and drivers to the implementation of onshore power supply - a literature review. Sustain Times 2022;14:6072. https://doi.org/10.3390/SU14106072. 2022;14:6072.

[46] Peng Y, Li X, Wang W, Wei Z, Bing X, Song X. A method for determining the allocation strategy of on-shore power supply from a green container terminal perspective. Ocean Coast Manag 2019;167:158–75. https://doi.org/10.1016/j.ocecoaman.2018.10.007.

[47] Sciberras EA, Zahawi B, Atkinson DJ, Juandó A, Sarasquete A. Cold ironing and onshore generation for airborne emission reductions in ports. Proc Inst Mech Eng Part M J Eng Marit Environ 2016;230:67–82. https://doi.org/10.1177/1475090214532451.

[48] Peng C. Application of shore power for ocean going vessels at berth in China. DEStech Trans Environ Energy Earth Sci 2016;8–15. https://doi.org/10.12783/dteees/seeie2016/4489.

[49] Peng Y. The research on the optimal allocation of low-carbon seaport resources under uncertainties. Dalian: Dalian University of Technology; 2016.

[50] Iris Ç, Lam JSL. Optimal energy management and operations planning in seaports with smart grid while harnessing renewable energy under uncertainty. Omega 2021;103:102445. https://doi.org/10.1016/J.OMEGA.2021.102445.

[51] Colarossi D, Lelow G, Principi P. Local energy production scenarios for emissions reduction of pollutants in small-medium ports. Transp Res Interdiscip Perspect 2022;13:100554. https://doi.org/10.1016/J.TRIP.2022.100554.

[52] Ahamad NB, Othman M, Vasquez JC, Guerrero JM, Su CL. Optimal sizing and performance evaluation of a renewable energy based microgrid in future seaports. Proc IEEE Int Conf Ind Technol 2018;2018. https://doi.org/10.1109/ICIT.2018.8352322. Febru:1043–8.

[53] Stępień Z. A comprehensive overview of hydrogen-fueled internal combustion engines: achievements and future challenges. Energies 2021;14:6504. https://doi.org/10.3390/EN14206504. 2021;14:6504.

[54] Giacomazzi E, Messina G. Hydrogen and the fuel-flexibility dilemma in gas turbines n.d. https://doi.org/10.12910/EAI2021-024.

[55] Sembler WJ, Kumar S, Palmer D. Fuel cells as an alternative to cold ironing. J Fuel Cell Sci Technol 2009;6. https://doi.org/10.1115/1.3006305. 0310091–03100911.

[56] Barone G, Buonomano A, Forzano C, Palombo A. Implementing the dynamic simulation approach for the design and optimization of ships energy systems: methodology and applicability to modern cruise ships. Renew Sustain Energy Rev 2021;150:111488. https://doi.org/10.1016/J.RSER.2021.111488.

[57] Al-Enazi A, Okonkwo EC, Bicer Y, Al-Ansari T. A review of cleaner alternative fuels for maritime transportation. Energy Rep 2021;7. https://doi.org/10.1016/J.EGYR.2021.03.036. 1962–85.

[58] International Maritime Organization (IMO). Cutting sulphur oxide emissions n.d. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx (accessed November 8, 2022).

[59] Sim J. A carbon emission evaluation model for a container terminal. J Clean Prod 2018;186:526–33. https://doi.org/10.1016/J.JCLEPRO.2018.03.170.

[60] Andersson K, Salazar M. Methanol as a marine fuel report. 2018.

[61] Burel F, Taccani R, Zuliani N. Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion. Energy 2013;57:412–20. https://doi.org/10.1016/J.ENERGY.2013.05.002.

[62] Baldi F, Coraddu A, Mondejar ME. Sustainable energy systems on ships: novel technologies for low carbon shipping. Sustain Energy Syst Ships Nov Technol Low Carbon Shipp 2022:1–533. https://doi.org/10.1016/C2020-0-01975-4.

[63] Ushakov S, Stenersen D, Einang PM. Methane slip from gas fuelled ships: a comprehensive summary based on measurement data. J Mar Sci Technol 2019;24:1308–25. https://doi.org/10.1007/S00773-018-00622-Z/FIGURES/15.

[64] Det Norske Veritas (Dnv). Alternative Fuels Insights for the shipping industry n.d. https://www.dnv.com/services/alternative-fuels-insight-128171 (accessed November 8, 2022).

[65] Zhou Y, Pavlenko N, Rutherford D, Osipova L, Comer B, Bates J, et al. The potential of liquid biofuels in reducing ship. emissions 2020.

[66] van Biert L, Mrozewski K, Hart P. Inventory of the application of fuel cells in the MARitime sector (FCMAR) project data. 2021.

[67] Brynolf S, Fridell E, Andersson K. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. J Clean Prod 2014;74:86–95. https://doi.org/10.1016/J.JCLEPRO.2014.03.052.

[68] Zamfirescu C, Dincer I. Using ammonia as a sustainable fuel. J Power Sources 2008;185:459–65. https://doi.org/10.1016/J.JPOWSOUR.2008.02.097.

[69] Chehade G, Dincer I. Progress in green ammonia production as potential carbon-free fuel. Fuel 2021;299:120845. https://doi.org/10.1016/J.FUEL.2021.120845.

[70] Kim K, Roh G, Kim W, Chun K. A preliminary study on an alternative ship propulsion system fueled by ammonia: environmental and economic assessments. J Mar Sci Eng 2020;8:183. https://doi.org/10.3390/JMSE8030183. 2020;8:183.

[71] 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.

[72] Ammonia Fuel Bunkering Network, Ocean Hyway Cluster n.d. https://www.oceanhywaycluster.no/projectlist/prosjektnamn-48faf (accessed November 8, 2022).

[73] Azane Fuel Solutions n.d. https://www.azanefs.com/(accessed November 8, 2022).

[74] Salmon N, Bañares-Alcántara R, Nayak-Luke R. Optimization of green ammonia distribution systems for intercontinental energy transport. iScience 2021;24:102903. https://doi.org/10.1016/J.ISCI.2021.102903.

[75] Det Norske Veritas (DNV). Assessment of selected alternative fuels and technologies. 2019.

[76] Pivetta D, Dall'Armi C, Taccani R. Multi-objective optimization of a hydrogen hub for the decarbonization of a port industrial area. J Mar Sci Eng 2022;10(2):231. https://doi.org/10.3390/jmse10020231.

[77] van Biert L, Godjevac M, Visser K, Aravind PV. A review of fuel cell systems for maritime applications. J Power Sources 2016;327:345–64. https://doi.org/10.1016/j.jpowsour.2016.07.007.

[78] 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.

[79] Dall'Armi C, Pivetta D, Taccani R. Hybrid PEM Fuel Cell Power Plants Fuelled by Hydrogen for Improving Sustainability in Shipping: State of the Art and Review on Active Projects. Energies 2023;16(4):2022. https://doi.org/10.3390/en16042022.

[80] Raucci C. The potential of hydrogen to fuel international shipping. Dr Thesis, UCL (University Coll London); 2017.

[81] Wu P, Bucknall R. Hybrid fuel cell and battery propulsion system modelling and multi-objective optimisation for a coastal ferry. Int J Hydrogen Energy 2020;45:3193–208. https://doi.org/10.1016/J.IJHYDENE.2019.11.152.

[82] Pivetta D, Dall'Armi C, Taccani R. Multi-objective optimization of hybrid PEMFC/Li-ion battery propulsion systems for small and medium size ferries. Int J Hydrogen Energy 2021;46:35949–60. https://doi.org/10.1016/J.IJHYDENE.2021.02.124.

[83] Dall'Armi C, Pivetta D, Taccani R. Uncertainty analysis of the optimal health-conscious operation of a hybrid PEMFC coastal ferry. Int J Hydrogen Energy 2022;47:11428–40. https://doi.org/10.1016/J.IJHYDENE.2021.10.271.

[84] Taccani R, Malabotti S, Dall'Armi C, Micheli D. High energy density storage of gaseous marine fuels: an innovative concept and its application to a hydrogen powered ferry. Int Shipbuild Prog 2020;67:33–56. https://doi.org/10.3233/ISP-190274.

[85] Baldi F, Azzi A, Maréchal F. From renewable energy to ship fuel: ammonia as an energy vector and mean for energy storage. Comput Aided Chem Eng 2019;46:1747–52. https://doi.org/10.1016/B978-0-12-818634-3.50292-7.

[86] Böhm M, Fernández Del Rey A, Pagenkopf J, Varela M, Herwartz-Polster S, Nieto Calderón B. Review and comparison of worldwide hydrogen activities in the rail sector with special focus on on-board storage and refueling technologies. Int J Hydrogen Energy 2022;47:38003–17. https://doi.org/10.1016/J.IJHYDENE.2022.08.279.

[87] Yusaf T, Fernandes L, Talib ARA, Altarazi YSM, Alrefae W, Kadirgama K, et al. Sustainable aviation, hydrogen is the future. Sustain Times 2022;14. https://doi.org/10.3390/SU14010548. 548 2022;14:548.

[88] Sadiq M, Ali SW, Terriche Y, Mutarraf MU, Hassan MA, Hamid K, et al. Future greener seaports: a review of new infrastructure, challenges, and energy efficiency measures. IEEE Access 2021;9:75568–87. https://doi.org/10.1109/ACCESS.2021.3081430.

[89] Zanne M, Twrdy E, Beškovnik B. The effect of port gate location and gate procedures on the port-city relation. Sustain Times 2021;13. https://doi.org/10.3390/su13094884.

[90] Molavi A, Lim GJ, Race B. A framework for building a smart port and smart port index. Int J Sustain Transp 2020;14:686–700. https://doi.org/10.1080/15568318.2019.1610919.

[91] Boile M, Theofanis S, Sdoukopoulos E, Plytas N. Developing a port energy management plan: issues, challenges, and prospects. Transport Res Rec 2016;2549:19–28. https://doi.org/10.3141/2549-03.

[92] Wen B, Xia W, Sokolovic JM. Recent advances in effective collectors for enhancing the flotation of low rank/oxidized coals. Powder Technol 2017;319:1–11. https://doi.org/10.1016/J.POWTEC.2017.06.030.

[93] Steenken D, Voß S, Stahlbock R. Container terminal operation and operations research-a classification and literature review n.d.. https://doi.org/10.1007/s00291-003-0157-z.

[94] Carlo HJ, Vis IFA, Roodbergen KJ. Transport operations in container terminals: literature overview, trends, research directions and classification scheme. Eur J Oper Res 2014;236:1–13. https://doi.org/10.1016/J.EJOR.2013.11.023.

[95] Rina S.p.A. Green cranes n.d. https://www.rina.org/en/media/CaseStudies/GREENCRANES (accessed November 8, 2022).

[96] Mac Kinnon M, Zhu S, Cervantes A, Dabdub D, Samuelsen GS. Benefits of near-zero freight: The air quality and health impacts of low-NOx compressed natural gas trucks. Https://DoiOrg/101080/1096224720211957727 2021;vol. 71:1428–44. https://doi.org/10.1080/10962247.2021.1957727..

[97] International Renewable Energy Agency (IRENA). Global hydrogen trade to meet the 1.5°C climate goal: green hydrogen cost and potential. 2022.

[98] Misra A, Venkataramani G, Gowrishankar S, Ayyasam E, Ramalingam V. 101080/10485236201711907880. Renewable energy based smart microgrids—a pathway to green port development, vol. 37; 2017. https://doi.org/10.1080/10485236.2017.11907880. 17–32.

[99] Alamoush AS, Ballini F, Ölçer AI. Ports' technical and operational measures to reduce greenhouse gas emission and improve energy efficiency: a review. Mar Pollut Bull 2020;160:111508. https://doi.org/10.1016/j.marpolbul.2020.111508.

[100] Comini R., Cortella G. Energetica generale. 4th ed. S.G.E. 2005.

[101] The BMW Hydrogen 7 n.d. https://www.press.bmwgroup.com/united-kingdom/article/detail/T0014470EN_GB/the-bmw-hydrogen-7?language=en_GB (accessed November 8, 2022).

[102] Hogerwaard J, Dincer I. Comparative efficiency and environmental impact assessments of a hydrogen assisted hybrid locomotive. Int J Hydrogen Energy 2016;41:6894–904. https://doi.org/10.1016/J.IJHYDENE.2016.01.118.

[103] Cmb TECH. Hydrotug dual-fuel tugboat n.d. https://cmb.tech/hydrotug-project (accessed November 8, 2022).

[104] Yadav A, Jeong B. Safety evaluation of using ammonia as marine fuel by analysing gas dispersion in a ship engine room using CFD. J Int Marit Safety, Environ Aff Shipp 2022;6:99–116. https://doi.org/10.1080/25725084.2022.2083295.

[105] Kim J, Rahimi M, Newell J. Life-cycle emissions from port electrification: a case study of cargo handling tractors at the port of Los Angeles. Int J Sustain Transp 2012;6:321–37. https://doi.org/10.1080/15568318.2011.606353.

[106] Hoang AT, Foley AM, Nižetić S, Huang Z, Ong HC, Ölçer AI, et al. Energy-related approach for reduction of CO2 emissions: a critical strategy on the port-to-ship pathway. J Clean Prod 2022;355:131772. https://doi.org/10.1016/J.JCLEPRO.2022.131772.

[107] Trans-European Transport Network (Ten-T) n.d. https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_en. [Accessed 8 November 2022].

[108] Kanellos NV, Zhang X. Determinants for the uptake of alternatively fuelled HGVs: towards a maturity framework. Conf Pap 2022. https://doi.org/10.21427/d1m9-7660. 10–3.

[109] Antonelli M, Ceraolo M, Desideri U, Lutzemberger G, Sani L. Hybridization of rubber tired gantry (RTG) cranes. J Energy Storage 2017;12:186–95. https://doi.org/10.1016/J.EST.2017.05.004.

[110] Zhao N, Schofield N, Niu W, Suntharalingam P, Zhang Y. Hybrid power-train for port crane energy recovery. IEEE Transp Electrif Conf Expo, ITEC Asia-Pacific 2014 - Conf Proc 2014. https://doi.org/10.1109/ITEC-AP.2014.6941043.

[111] Niu W, Huang X, Yuan F, Schofield N, Xu L, Chu J, et al. Sizing of energy system of a hybrid lithium battery RTG crane. IEEE Trans Power Electron 2017;32:7837–44. https://doi.org/10.1109/TPEL.2016.2632202.

[112] Wei HL, Gu W, Chu JX. The dynamic power control technology for the high power lithium battery hybrid rubber-tired gantry (RTG) crane. IEEE Trans Ind Electron 2019;66:132–40. https://doi.org/10.1109/TIE.2018.2816011.

[113] Skeletontech - Industrial Applications n.d. https://www.skeletontech.com/industrial-applications (accessed November 9, 2022).

[114] H2Ports - Clean Hydrogen Partnership n.d. https://h2ports.eu/(accessed November 9, 2022).

[115] Terberg Special Vehicles n.d. https://www.terbergspecialvehicles.com/en (accessed November 9, 2022).

[116] Chang CC, Huang PC, Tu JS. Life cycle assessment of yard tractors using hydrogen fuel at the Port of Kaohsiung, Taiwan. Energy 2019;189:116222. https://doi.org/10.1016/j.energy.2019.116222.

[117] International Energy Agency (IEA). The Future of Rail n.d. https://www.iea.org/reports/the-future-of-rail (accessed November 8, 2022).

[118] Al-Hamed KHM, Dincer I. Comparative evaluation of fuel cell based powering systems for cleaner locomotives. Therm Sci Eng Prog 2021;23:100912. https://doi.org/10.1016/J.TSEP.2021.100912.

[119] Al-Hamed KHM, Dincer I. A novel ammonia solid oxide fuel cell-based powering system with on-board hydrogen production for clean locomotives. Energy 2021;220:119771. https://doi.org/10.1016/J.ENERGY.2021.119771.

[120] Cullen DA, Neyerlin KC, Ahluwalia RK, Mukundan R, More KL, Borup RL, et al. New roads and challenges for fuel cells in heavy-duty transportation. Nat Energy 2021;6:462–74. https://doi.org/10.1038/s41560-021-00775-z.

[121] Smallbone A, Jia B, Atkins P, Roskilly AP. The impact of disruptive powertrain technologies on energy consumption and carbon dioxide emissions from heavy-duty vehicles. Energy Convers Manag X 2020;6:100030. https://doi.org/10.1016/J.ECMX.2020.100030.

[122] Espina-Valdés R, Álvarez Álvarez E, García-Maribona J, Trashorras AJG, González-Caballín JM. Tidal current energy potential assessment in the Avilés Port using a three-dimensional CFD method. Clean Technol Environ Policy 2019;21:1367–80. https://doi.org/10.1007/S10098-019-01711-2/FIGURES/23.

[123] Ramos V, Carballo R, Álvarez M, Sánchez M, Iglesias G. A port towards energy self-sufficiency using tidal stream power. Energy 2014;71:432–44. https://doi.org/10.1016/J.ENERGY.2014.04.098.

[124] Vicinanza D, Lauro E Di, Contestabile P, Gisonni C, Lara JL, Losada IJ. Review of innovative harbor breakwaters for wave-energy conversion. J Waterw Port, Coast Ocean Eng 2019;145:03119001. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000519.

[125] Li L, Zhu J, Ye G, Feng X. Development of green ports with the consideration of coastal wave energy. Sustain Times 2018;10. https://doi.org/10.3390/SU10114270. 4270 2018;10:4270.

[126] Cascajo R, García E, Quiles E, Correcher A, Morant F. Integration of marine wave energy converters into seaports: a case study in the port of Valencia. Energies 2019;12:787. https://doi.org/10.3390/EN12050787. 2019;12:787.

[127] Kang D, Kim S. Conceptual model development of sustainability practices: the case of port operations for collaboration and governance. Sustain Times 2017;9:1–15. https://doi.org/10.3390/su9122333.

[128] Acciaro M, Ghiara H, Cusano MI. Energy management in seaports: a new role for port authorities. Energy Pol 2014;71:4–12. https://doi.org/10.1016/J.ENPOL.2014.04.013.

[129] Cordis - European Commission. Green and effective operations at terminals and in ports (GREEN EFFORTS). n.d. https://cordis.europa.eu/project/id/285687 (accessed November 1, 2023).

[130] Delnooz A, Six D, Kessels K, E-harbours Hommelberg MPF. Identification and analysis of barriers for virtual power plants in harbour regions. 9th Int Conf Eur Energy Mark EEM 2012;12. https://doi.org/10.1109/EEM.2012.6254682.

[131] Hentschel M, Ketter W, Collins J. Renewable energy cooperatives: facilitating the energy transition at the Port of Rotterdam. Energy Pol 2018;121:61–9. https://doi.org/10.1016/J.ENPOL.2018.06.014.

[132] H-vision webpage n.d. https://www.h-vision.nl/en. [Accessed 9 November 2022].

[133] Hydrogen - Groningen Seaports nd. https://www.groningen-seaports.com/en/hydrogen/. [Accessed 9 November 2022].

[134] Manolis N, Ahmad I, Fotios K, Palensky P, Gawlik W. MAS based demand response application in port city using reefers. Commun Comput Inf Sci 2017;722:361–70. https://doi.org/10.1007/978-3-319-60285-1_31/COVER.

[135] Prousalidis J, Antonopoulos G, Patsios C, Greig A, Bucknall R. Green shipping in emission controlled areas: combining smart grids and cold ironing. IEEE; 2014.

[136] Wang W, Peng Y, Li X, Qi Q, Feng P, Zhang Y. A two-stage framework for the optimal design of a hybrid renewable energy system for port application. Ocean Eng 2019;191:106555. https://doi.org/10.1016/J.OCEANENG.2019.106555.

[137] Shell LNG Outlook 2022 | Shell Global n.d. https://www.shell.com/energy-and-innovation/natural-gas/liquefied-natural-gas-lng/lng-outlook-2022.html#iframe=L3dlYmFwcHMvTE5HX291dGxvb2tfMjAyMi8 (accessed November 8, 2022).

[138] Notteboom T, Pallis A, Rodrigue J-P. Chapter 8.3 – ports and energy. 2021.

[139] COAG Energy Council Hydrogen Working Group. Australia's national hydrogen strategy. 2019.

[140] Gobierno de Chile - national green hydrogen strategy; 2020. n.d. energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf (accessed November 1, 2023).

[141] Hydrogen strategy for Canada; 2020. n.d. https://natural-resources.canada.ca/climate-change-adapting-impacts-and-reducing-emissions/canadas-green-future/the-hydrogen-strategy/23080 (accessed November 1, 2023).

[142] Netherlands - government strategy on hydrogen. n.d. https://doi.org/https://www.government.nl/documents/publications/2020/04/06/government-strategy-on-hydrogen.

[143] Incer-Valverde J, Patiño-Arévalo LJ, Tsatsaronis G, Morosuk T. Hydrogen-driven Power-to-X: state of the art and multicriteria evaluation of a study case. Energy Convers Manag 2022;266:115814. https://doi.org/10.1016/J.ENCONMAN.2022.115814.

[144] Hank C, Gelpke S, Schnabl A, White RJ, Full J, Wiebe N, et al. Economics & carbon dioxide avoidance cost of methanol production based on renewable hydrogen and recycled carbon dioxide – power-to-methanol. Sustain Energy Fuels 2018;2:1244–61. https://doi.org/10.1039/C8SE00032H.

[145] Hank C, Sternberg A, Köppel N, Holst M, Smolinka T, Schaadt A, et al. Energy efficiency and economic assessment of imported energy carriers based on renewable electricity. Sustain Energy Fuels 2020;4:2256–73. https://doi.org/10.1039/D0SE00067A.

[146] Bargiacchi E, Antonelli M, Desideri U. A comparative assessment of Power-to-Fuel production pathways. Energy 2019;183:1253–65. https://doi.org/10.1016/J.ENERGY.2019.06.149.

[147] 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.

[148] Kolb S, Müller J, Luna-Jaspe N, Karl J. Renewable hydrogen imports for the German energy transition – a comparative life cycle assessment. J Clean Prod 2022;373:133289. https://doi.org/10.1016/J.JCLEPRO.2022.133289.

[149] Eckl F, Eltrop L, Moita A, Costa Neto R. Techno-economic evaluation of two hydrogen supply options to southern Germany: on-site production and import from Portugal. Int J Hydrogen Energy 2022;47:25214–28. https://doi.org/10.1016/J.IJHYDENE.2022.05.266.

[150] Hjeij D, Biçer Y, Koç M. Hydrogen strategy as an energy transition and economic transformation avenue for natural gas exporting countries: Qatar as a case study. Int J Hydrogen Energy 2022;47:4977–5009. https://doi.org/10.1016/J.IJHYDENE.2021.11.151.

[151] Burandt T. Analyzing the necessity of hydrogen imports for net-zero emission scenarios in Japan. Appl Energy 2021;298:117265. https://doi.org/10.1016/J.APENERGY.2021.117265.

[152] Bakar NNA, Guerrero JM, Vasquez JC, Bazmohammadi N, Yu Y, Abusorrah A, et al. A review of the conceptualization and operational management of seaport microgrids on the shore and seaside. Energies 2021;14:1–31. https://doi.org/10.3390/en14237941.

[153] Debouza M, Al-Durra A, El-Fouly THM, Zeineldin HH. Survey on microgrids with flexible boundaries: strategies, applications, and future trends. Elec Power Syst Res 2022;205:107765. https://doi.org/10.1016/j.epsr.2021.107765.

[154] Mousavi SYM, Jalilian A, Savaghebi M, Guerrero JM. Flexible compensation of voltage and current unbalance and harmonics in microgrids. Energies 2017;10:1–19. https://doi.org/10.3390/en10101568.

[155] Yigit K, Acarkan B. A new electrical energy management approach for ships using mixed energy sources to ensure sustainable port cities. Sustain Cities Soc 2018;40:126–35. https://doi.org/10.1016/j.scs.2018.04.004.

[156] Vahedipour-Dahraie M, Rashidizadeh-Kermani H, Anvari-Moghaddam A, Siano P, Catalão JPS. Short-term reliability and economic evaluation of resilient microgrids under incentive-based demand response programs. Int J Electr Power Energy Syst 2022;138. https://doi.org/10.1016/j.ijepes.2021.107918.

[157] Cao Y, Mohammadzadeh A, Tavoosi J, Mobayen S, Safdar R, Fekih A. A new predictive energy management system: deep learned type-2 fuzzy system based on singular value decommission. Energy Rep 2022;8:722–34. https://doi.org/10.1016/j.egyr.2021.12.012.

[158] Jeyaraj PR, Asokan SP, Karthiresan AC. Optimum power flow in DC microgrid employing bayesian regularized deep neural network. Elec Power Syst Res 2022;205:107730. https://doi.org/10.1016/j.epsr.2021.107730.

[159] Sifakis N, Konidakis S, Tsoutsos T. Hybrid renewable energy system optimum design and smart dispatch for nearly Zero Energy Ports. J Clean Prod 2021;310:127397. https://doi.org/10.1016/j.jclepro.2021.127397.

[160] Ren M, Lu P, Liu X, Hossain MS, Fang Y, Hanaoka T, et al. Decarbonizing China's iron and steel industry from the supply and demand sides for carbon neutrality. Appl Energy 2021;298:117209. https://doi.org/10.1016/j.apenergy.2021.117209.

[161] Muslemani H, Liang X, Kaesehage K, Ascui F, Wilson J. Opportunities and challenges for decarbonizing steel production by creating markets for 'green steel' products. J Clean Prod 2021:315. https://doi.org/10.1016/j.jclepro.2021.128127.

[162] Sgouridis S, Ali M, Sleptchenko A, Bouabid A, Ospina G. Aluminum smelters in the energy transition: optimal configuration and operation for renewable energy integration in high insolation regions. Renew Energy 2021;180:937–53. https://doi.org/10.1016/j.renene.2021.08.080.

[163] Manna J, Jha P, Sarkhel R, Banerjee C, Tripathi AK, Nouni MR. Opportunities for green hydrogen production in petroleum refining and ammonia synthesis industries in India. Int J Hydrogen Energy 2021;46:38212–31. https://doi.org/10.1016/j.ijhydene.2021.09.064.

[164] Rajabloo T, De Ceuninck W, Van Wortswinkel L, Rezakazemi M, Aminabhavi T. Environmental management of industrial decarbonization with focus on chemical sectors: a review. J Environ Manag 2022;302:114055. https://doi.org/10.1016/j.jenvman.2021.114055.

[165] Zier M, Stenzel P, Kotzur L, Stolten D. A review of decarbonization options for the glass industry. Energy Convers Manag X 2021;10:100083. https://doi.org/10.1016/j.ecmx.2021.100083.

[166] Röben FTC, Schöne N, Bau U, Reuter MA, Dahmen M, Bardow A. Decarbonizing copper production by power-to-hydrogen: a techno-economic analysis. J Clean Prod 2021:306. https://doi.org/10.1016/j.jclepro.2021.127191.

[167] Wang J, Kang L, Liu Y. Optimal design of a cooperated energy storage system to balance intermittent renewable energy and fluctuating demands of hydrogen and oxygen in refineries. Comput Chem Eng 2021;155:107543. https://doi.org/10.1016/j.compchemeng.2021.107543.

[168] Nurdiawati A, Urban F. Energy Research & Social Science Decarbonising the refinery sector : a socio-technical analysis of advanced biofuels , green hydrogen and carbon capture and storage developments in Sweden. Energy Res Social Sci 2022;84:102358. https://doi.org/10.1016/j.erss.2021.102358.

[169] World Shipping Council n.d https://www.worldshipping.org/ (accessed August 3, 2023).

[170] International Energy Agency (IEA). IEA Task 39: Hydrogen in the maritime n.d. https://www.ieahydrogen.org/wp-admin/admin-ajax.php?juwpfisadmin=false&action=wpfd&task=file.download&wpfd_category_id=17&wpfd_file_id=3991&token=abad9fa9a0f0a9c00152edff03825bf4&preview=1 (accessed November 9, 2022).

[171] International Energy Agency (IEA). Hydrogen Projects Database n.d. https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database (accessed August 3, 2023).

[172] Horizon Europe n.d. https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en (accessed July 24, 2023)..

[173] Hydrogen refuelling station Delfzijl - PitPoint clean fuels n.d. 21; November 2022. https://www.pitpointcleanfuels.com/cases/hydrogen-refuelling-delfzijl/(accessed.

[174] Port of Antwerp-Bruges n.d https://www.portofantwerpbruges.com/en (accessed November 21, 2022).

[175] Port of Antwerp. Orders World's First Hydrogen-Powered Tug - Offshore Energy n.d. https://www.offshore-energy.biz/port-of-antwerp-orders-worlds-first-hydrogen-powered-tug/ (accessed November 21, 2022).

[176] Port-jérôme-sur-seine, the city entrance of a territory in transition. n.d. https://www.europan-europe.eu/media/default/0001/17/e15_fr_port_jerome_t_en_pdf.pdf (accessed November 1, 2023).

[177] The push boat with a whole new energy system – BEHALA n.d.. https://www.behala.de/en/the-push-boat-with-a-whole-new-energy-system/(accessed November 21, 2022).

[178] Port of Los Angeles. Port of Los Angeles Preliminarily Awarded $41 Million from California Air Resources Board to Launch Zero Emissions Hydrogen-Fuel-Cell-Electric Freight Project n.d. https://www.portoflosangeles.org/references/news_091418_carb_toyota (accessed November 21, 2022).

[179] Ports of Auckland (POAL) - Sustainability n.d.. https://www.poal.co.nz/sustainability (accessed November 21, 2022).

[180] HESC Project n.d.. https://www.hydrogenenergysupplychain.com/(accessed November 21, 2022).

[181] Hydrogen in Rotterdam - Port of Rotterdam n.d https://www.portofrotterdam.com/en/port-future/energy-transition/ongoing-projects/hydrogen-rotterdam (accessed November 9, 2022].

[182] Air Liquide. Air Liquide receives support from Dutch State for two large-scale electrolyzer projects in the Netherlands n.d. https://www.airliquide.com/group/press-releases-news/2022-12-21/air-liquide-receives-support-dutch-state-two-large-scale-electrolyzer-projects-netherlands (accessed July 24, 2023).

[183] Green Flamingo Project n.d. https://meethydrogen.com/resource/green-flamingo-project-how-portugal-could-export-green-hydrogen-to-european-union (accessed November 9, 2022).

[184] International Energy Agency (IEA). Hydrogen in north-western Europe - a vision towards 2030. 2021.

[185] Port of Valencia. The Port of Valencia now has its hydrogen plant n.d.. https://www.valenciaport.com/en/the-port-of-valencia-now-has-its-hydrogen-plant/ (accessed November 9, 2022).

[186] Port of Los Angeles. Toyota and Kenworth partner on hydrogen fuel cell Class 8 trucks. https://ajot.com/insights/full/ai-port-of-los-angeles-toyota-and-kenworth-partner-on-hydrogen-fuel-cell-class-8-trucks (accessed November 9, 2022).

[187] Leo T. Distributed Hydrogen Production Lowering the cost and carbon footprint of hydrogen production. globally 2022.

[188] Global Mitsubishi Heavy Industries Ltd. Mitsubishi Heavy Industries Partner in Newly Established Hamburg Hydrogen Network to 'Make Hamburg Greener' n.d. https://www.mhi.com/news/21042602.html (accessed November 9, 2022).

[189] Port of Hamburg website n.d. https://www.hafen-hamburg.de/en/homepage/ (accessed November 9, 2022).

[190] Hamburg Green Hydrogen Hub (HGHH) project n.d.. https://www.hghh.eu/en (accessed November 9, 2022).

[191] H2LOAD project n.d. https://hhla.de/innovation/wasserstoff/h2load (accessed November 9, 2022).

[192] HHLA. Newly Established Hamburg Hydrogen Network to 'Make Hamburg Greener' n.d. https://hhla.de/en/media/news/detail-view/newly-established-hamburg-hydrogen-network-to-make-hamburg-greener (accessed November 9, 2022).

[193] EEHH Projects - Hydrogen Hamburg n.d. https://www.h2-hh.de/en/projects.html (accessed November 9, 2022).

[194] Twelve Companies Join Forces To Form The Hamburg Hydrogen Network n.d. https://fuelcellsworks.com/news/twelve-companies-join-forces-to-form-the-hamburg-hydrogen-network/(accessed November 9, 2022).

[195] Hydroports present to Dutch Government n.d. https://www.h2-view.com/story/hydroports-present-to-dutch-government/(accessed November 9, 2022).

[196] Wadden Sea Ports website n.d.. https://waddenseaports.com/(accessed November 9, 2022).

[197] NortH2 project - kickstarting the green hydrogen economy n.d. https://www.north2.eu/en/(accessed November 9, 2022).

[198] Heavenn project - H2 Energy Applications in Valley Environments for Nothern Netherlands n.d. https://heavenn.org/(accessed November 9, 2022).

[199] Chemistry Park Delfzijl website n.d. https://www-chemieparkdelfzijl-nl.translate.goog/?_x_tr_sl=nl&_x_tr_tl=en&_x_tr_hl=nl (accessed November 9, 2022).

[200] Djewels project n.d. https://djewels.eu/(accessed November 9, 2022).

[201] H2Ships project n.d.https://h2ships.org/(accessed November 9, 2022).