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EDITORIAL

Seaports as green hydrogen hubs: advances, opportunities and challenges in Europe

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1 Introduction

The energy transition from fossil fuels to renewables is widely considered as a key action field in decarbonizing the global economy, thus preventing the disastrous, irreversible, consequences of climate change, too well known to all. Yet, the greatest part of the required energy in the coming decade will still come from fossil sources. Fortunately, however, the highest growth rate will be seen in renewable energy sources. The World Energy Outlook 2022 report of the International Energy Agency (IEA) summarizes the longer-term global energy mix. In the 'Stated Policies Scenario' (STEPS), coal demand will reach a peak within the next few years, natural gas reaches a plateau by the end of the 2020s, and oil demand reaches a peak by mid-2030s before it starts to decline. In relative terms, the share of fossil fuels (coal, oil, and natural gas) in total energy supply is expected to decrease from just under 80% in 2020 to slightly above 60% in 2040. The main scenario also shows that about 60% of all new power generation capacity to 2040 shall regard renewables (IEA 2022a). Under the more ambitious 'Announced Pledges Scenario' (APS), global energy demand is expected to increase by only 0.2% per annum to 2030 (0.8% p.a. in the STEPS) combined with a much stronger shift to low emission energy sources. The speed of transformation in the 'Net Zero Emissions by 2050' scenario (NZE) is even more dramatic.

In recent years, hydrogen (H_2) has attracted a lot of attention in the energy transition and decarbonization debate. According to IRENA (2022a), hydrogen is set

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to meet up to 12% of global energy demand by 2050. The transition to hydrogen is not merely a fuel replacement but a shift to a new system with political, technical, environmental, and economic disruptions. In Europe, hydrogen is hoped to play an essential role in the energy transition. Hydrogen accounts for less than 2% of Europe's present energy consumption and it is primarily used in the production of chemical products, such as plastics and fertilizers. 96% of hydrogen production is by means of natural gas. This is called *grey hydrogen*, using a process of steam methane reforming, where natural gas is mixed with very hot steam and a catalyst. *Blue hydrogen* is also hydrogen produced from natural gas, but this process is made carbon–neutral by capturing and storing the CO_2 emissions (also called Carbon Capture and Storage or CCS).

Green hydrogen can be obtained via electrolysis, i.e., the use of (renewable) electricity to split water into hydrogen and oxygen. Green hydrogen has made an undulating movement as an alternative energy source in the past decades; it came and disappeared from the radar again and again. The latest wave, however, has been massive, with large investment budgets and countless projects being released. Green hydrogen has no carbon impacts, as the energy used to power electrolysis comes primarily from renewable sources like wind, water or solar. The use of green hydrogen as a raw material and fuel can thus reduce emissions in industry and make a major contribution to the 2030 and 2050 climate targets. When produced at times and places where solar and wind energy resources are abundantly available, renewable hydrogen can also support the electricity sector, providing long-term and large-scale storage, as well as improving the flexibility of energy systems by balancing supply and demand.

While the interest in hydrogen solutions in the 2010s was mostly driven by oil price shocks and concerns about peak oil demand or air pollution, the current interest in hydrogen seems to be primarily driven by a heightened focus on net-zero emissions, combined with a dramatic decrease in the costs of renewable electricity[1] and a recent cost surge in fossil fuels due to geopolitical tensions and the war in Ukraine. Still, demand for green hydrogen is expected to really take off only in the mid-2030s. By that time, green hydrogen should have become cost-compete with fossil-fuel hydrogen globally, and this is poised to happen even earlier in some countries like China, Brazil, and India.

This editorial focuses on the potential impact of green hydrogen on seaports and the things the latter should do in anticipation. We particularly explore the critical challenges and opportunities green hydrogen can bring to the economics and governance of seaports. We start the debate by discussing the fast-growing public and private interest in green hydrogen as part of the energy transition trajectory. Then, we analyze key considerations when placing green hydrogen in a seaport context. These range from the role of green hydrogen in the changing energy landscape of ports and the geo-economic repercussions of the adoption of green hydrogen on a port's cargo flows, to the role of seaports in driving down the costs of a green hydrogen economy vis à vis those of a fossil-based economy. We conclude this editorial

[1] IRENA (2022b) demonstrates that the cost of renewable electricity decreased by 88% for solar PV, 68% for onshore wind and 60% for offshore wind from 2010 to 2021.

with a detailed discussion on the role of landlord port authorities in the adoption of green hydrogen as part of the energy transition.

2 All eyes on green hydrogen?

The strong focus on green hydrogen is visible both in the private and the public sector. By mid-2022, more than 1500 hydrogen-related projects were announced globally, while more than 60 countries have already developed or are developing hydrogen strategies (IRENA 2022c).

There has been strong regulatory and political support in recent years, particularly in Europe. For a long time, European policy was unclear about the potential role of renewable hydrogen in the energy transition and decarbonization debate. In recent years, the European Union has created a new momentum. In July 2020, the European Commission launched a strategy for energy systems integration and a separate *hydrogen strategy*. The Commission identifies the necessary steps for making renewable and low carbon hydrogen a key commodity in the energy system. The EU's hydrogen strategy explores the potential for renewable hydrogen to help decarbonize the EU in a cost-effective way and in line with the European Green Deal. The strategy puts forward a vision for the creation of a European hydrogen ecosystem, from research and innovation, to scale up production and infrastructure, to an international dimension. In the same month, the *European Clean Hydrogen Alliance* was created to support the large-scale deployment of clean hydrogen technologies by 2030, by bringing together renewable and low carbon hydrogen production, industry demand, transportation (among other sectors), and hydrogen transmission and distribution. In July 2021, the European Commission proposed the revision of the *RED II* (Directive (EU) 2018/2001) under the *Fit for 55* package of legislative proposals. The RED II directive sets targets for the use of renewable energy in transport fuels, basically requiring investments in green hydrogen-based fuels. Also, the *EU Green Deal* identifies hydrogen as one of the priorities in the energy transition.

The plan *REPowerEU*, initiated in 2022, gives further impetus to the hydrogen economy. The plan states that an additional 15 million tons (five of which produced in Europe with the remainder imported) of renewable hydrogen are required to replace imported Russian gas. The European five million would be additional to the 5 million tons already planned in *Fit for 55*. In September 2022, the European Union announced the setting up of a *European Hydrogen Bank* to help create a market for hydrogen. The bank will receive 3 billion euro in cash to bridge the investment gap and connect future supply and demand.

In September 2022, the European Commission also approved 5.2 billion euro of public support, by thirteen[2] Member States, for the *IPCEI Hy2Use* project. This is the second Important Project of Common European Interest (IPCEI) in the hydrogen value chain. The above amount is expected to unlock an additional 7 billion euro in private investments. Twentynine companies will participate in 35 projects

[2] Austria, Belgium, Denmark, Finland, France, Greece, Italy, the Netherlands, Poland, Portugal, Slovakia, Spain and Sweden.

concerning the construction of hydrogen-related infrastructure (large-scale electrolysers and transport infrastructure) and the development of innovative and more sustainable technologies for the integration of hydrogen into the industrial processes of many sectors. Various large-scale electrolysers are expected to be operational by 2024–2026, and many of the more innovative technologies deployed by 2026–2027. The completion of the overall project is planned for 2036, with timelines varying in function to the project and the companies involved (European Commission, press release 21 September 2022).

Since 2014, the European Investment Bank (EIB) has been providing significant support to hydrogen technologies: An overall investment of 1.2 billion euro, with over 550 million euro in direct financial support to technologies such as electrolysers, catalysts and fuel cells, and the co-financing of large-scale hydrogen production, carbon capture and storage, as well as hydrogen stations (EIB, press release 16 March 2022).

The growing focus on hydrogen has given impetus to the development of so-called *hydrogen valleys*. These are regional ecosystems that link hydrogen production, transportation, and various end-uses such as mobility or industrial feedstock. The valleys are considered important steps in enabling the development of a new 'hydrogen economy' (Roland Berger, 2021). To support the concept, a Hydrogen Valley Platform was set-up, commissioned by the European Union and developed by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU).[3] This global information sharing platform to date already features 32 global Hydrogen Valleys, spread over 21 countries, with a cumulative investment of more than 32.4 billion euro (data www.h2v.eu in late August 2022). Hydrogen valleys thus aim to build local hydrogen ecosystems. By 2050, there would be about 50 in the EU. Worldwide, this number is expected to reach 100 in 2030. There is a strong policy-backed focus of the private sector on technological innovations in, and the manufacturing of, equipment like electrolysers and fuel cells. The 2020s present a big race for technology leadership, as costs are likely to fall sharply with learning and scaling-up of needed infrastructure.

3 Green hydrogen as part of the changing port energy landscape

Quite a number of seaports play an essential role as importing or exporting energy hubs, handling large, fossil fuel flows of coal, crude oil and natural gas. The gas comes in, either via vessel (LNG carriers), using specialized deep-sea terminals, or

[3] FCH JU is a public private partnership supporting research, technological development and demonstration (RTD) activities in fuel cell and hydrogen energy technologies in Europe. The three members are the European Commission, fuel cell and hydrogen industries represented by Hydrogen Europe and the research community represented by Hydrogen Europe Research (http://www.fch.europa.eu).

via pipeline, ending in the port area. Seaports are often home to large energy plants.[4] The availability of land and cooling water, and the presence of large industrial customers, are some of the reasons for energy-producing firms to set up business in seaport areas. While many wind farms are installed offshore, or in open plots in the hinterland, a number of seaports are also home to wind farms, installed on breakwaters or narrow stretches of land close to the sea. The presence of power plants and power distribution infrastructure generates direct jobs and value-added, not only for the power plants themselves, but also for energy distribution platforms, and terminal operations (i.e., handling of coal, gas, and other fuels). The plant is also a major creator of jobs and value-added in other industries and services such as engineering firms, construction companies, maintenance and repair companies, survey and inspection firms, and security services.

The energy transition challenges existing energy hub ports, preparing them for a future decline in fossil-fuel-related activities, and for embracing the production, handling and storage of renewables, among which green hydrogen. Potentially, this may have far-reaching implications for ports. Green hydrogen is expected to assume a prominent role in an emerging new energy landscape in ports. Royal Haskoning (2022) presented 17 factsheets on this landscape and its impact on ports. Table 1 summarizes the potential physical impacts on port infrastructure, although the actual impacts will of course be port-specific. The table focuses on throughput, cargo handling and needed facilities (incl. grid, pipelines, road, rail, water) in the port, to service energy-related logistics (the text sections in italics in the second column show that hydrogen has a key role to play in 12 of the 17 aspects of the new energy landscape).

Indeed, ports can play a crucial role in the production and distribution of green hydrogen. They are important nodes, given existing and future local demand for hydrogen, the emerging offshore parks, and as junctions of transport nodes, some of which could shift to hydrogen or related fuels (e.g., vessels, barges, trucks). Additionally, the infrastructure and handling capabilities of seaports make them prime locations for the storage and distribution of hydrogen. Seaports can serve as hubs for the export of green hydrogen to other countries, helping to drive the global transition to clean energy.

Ports aiming for a strong position in green hydrogen are challenged to be active in all parts of the hydrogen value chain. A favorable location, a well-developed pipeline network, strong worldwide maritime connectivity, state-of-the-art terminal and logistics infrastructures, well-functioning and efficient industrial ecosystems and a strong customer base, are all important factors enabling a seaport to take up an important, pioneering, role in an emerging hydrogen economy, positioning itself as a hydrogen import, transit and production hub.

[4] Electricity is produced in conventional steam-electric plants (coal and lignite), conventional steam-electric plants (other fuels), combined-cycle and gas turbine plants, conventional hydroelectric plants, pumped-storage hydroelectric plants, nuclear power plants, waste-to-energy plants, biomass power plants, diesel and gas-engine power plants, wind energy plants, geothermal power plants and solar power plants.

Table 1 Seventeen aspects of the new energy landscape and potential impact on ports

	Main focus	Maritime transport	Water-way and IWT	Quays	Terminals	Storage	Port area networks	Hinterland connec-tions
A. Port								
A1. Energy saving	Lighting, energy storage/recovery systems, smart energy management technologies, energy efficiency improvements in buildings (such as upgrading insulation), and electrification of mobile equipment			x	x			
A2. Decarbonisation port equipment	Electrification through retrofitting or replacement of existing diesel port equipment with electric/hybrid drives. In the future, complementary to batteries, *low-to-zero carbon fuels such as hydrogen* (combined with a fuel cell or engine)			x	x		x	
A3. Onshore power supply (OPS)	Seagoing vessels and inland barges are (partially) supplied with electricity from shore. In the future, also batteries on board ships could be powered with OPS	x	x	x			x	
A4. Clean fuel bunkering	LNG, *liquid Hydrogen, Ammonia, and Methanol*, are currently foreseen as most likely maritime fuels. Regardless of which fuel, or combination of fuels, is chosen, ports must plan now (fuel availability, emission targets, safety and handling requirements)	x		x		x	x	
A5. On-site renewable power	Localised energy generation from renewable sources such as solar or wind. If linked with Energy Storage Systems (ESS), on site renewables can mitigate peak rate tariffs and provide ports with significant cost savings				x		x	

Table 1 (continued)

	Main focus	Maritime transport	Water-way and IWT	Quays	Terminals	Storage	Port area networks	Hinterland connec-tions
B. Wider port area								
B1. Waste to energy and chemicals	Incineration (combustion of waste with energy recovery) + waste-to-fuels + waste-to-chemicals. New and emerging technologies can produce energy from waste without direct combustion	x	x	x	x	x		x
B2. Offshore energy	Energy generated offshore is to typically integrated into onshore power systems (via electricity grid or gas). Two main challenges: (1) Distribution: expansion or upgrade of the current onshore networks; and (2) Storage: *land-side energy storage facilities need to balance the fluctuating supply and demand* and connection between offshore and onshore infrastructure						x	
B3. Offshore industry	Offshore wind farms (OWF): Europe has a total installed capacity of 25 GW. Targets: at least 60 GW by 2030, and 300 GW by 2050. *The transformation of (excess) wind power to hydrogen* may lead to additional energy infrastructure in ports, for example electrolysers converting power to hydrogen in the port, and pipelines bringing hydrogen produced offshore to the port and further inland	x	x	x	x	x	x	x

Table 1 (continued)

	Main focus	Maritime transport	Water-way and IWT	Quays	Terminals	Storage	Port area networks	Hinterland connec-tions
B4. Industry decarbonisation	Decarbonization of energy-intensive industries like refineries, steam crackers, *(gray) hydrogen and ammonia producers*, chemical and plastics industry, iron, steel and cement industry through electrification, improved heat integration, using renewable or bio-based fuels and feedstocks, make use of residual heat and/or adding Carbon Capture, Utilisation and Storage (CCUS, for example CO2 as a feedstock to producesynthetic fuels)	x	x			x	x	x
B5. Sustainable urban energy	Ports as energy hubs for the urban distribution of renewable electricity (wind and solar), *renewable fuels (e.g., hydrogen, bio-based fuels)*, renewable and/or residual heat and cooling						x	
B6. Energy conversion	The conversion between electrons and fuels, through power-to-gas and gas-to-power technologies for a reliable and flexible energy system and to provide carbon neutral fuels and feedstock. The *conversion of hydrogen to zero/low carbon fuels* also lead to the deployment of energy conversion infrastructure			x	x		x	x
B7. Energy storage hubs	(liquid) storage will play a key role in the energy transition. Fuels that may be transported in ships and impact ports: LNG, *Hydrogen in pure form (GH2 and LH2), Hydrogen carried in other liquids (liquid organic hydrogen carrier or LOHC), and in derived forms (Ammonia and Methanol)*		x	x	x	x	x	x

Table 1 (continued)

	Main focus	Maritime transport	Water-way and IWT	Quays	Terminals	Storage	Port area networks	Hinterland connec-tions
B8. CCUS	CCUS is currently one of few solutions available to tackle emissions from heavy or energy-intensive industries, the so-called hard-to-abatesectors, including those typically within or surrounding port areas. *For the start-up phase of large-scale hydrogen, it is expected that blue hydrogen combined with CCS will play a major part*				x	x	x	x
C. Economy & community								
C1. Zero-/low emission fuel supply chains	Zero/low carbon fuels can be used in industry as a feedstock or fuel, as a fuel for transportation, or as a heat source. *The most frequently mentioned fuels are green hydrogen, green ammonia, green methanol and biofuels*. Ports could play an active role as as facilitator, import/export, bunkering, storage, production, transit of zero/low carbon fuels and carbon capture of fossil fuels and/or *blue hydrogen*	x	x	x	x	x	x	x
C2. Zero-/low emission electron supply chains	Renewable power generation, mainly by means of solar and wind, requires the availability of a back-up system of conventional power plants. *Seasonal energy storage in the form of hydrogen* could help to decarbonise dispatchable power through gas turbines or fuel cells					x	x	x

Table 1 (continued)

	Main focus	Maritime transport	Waterway and IWT	Quays	Terminals	Storage	Port area networks	Hinterland connections
C3. Circular economy	In a full circular economy materials and resources will be used in closed loop systems which can still range over multiple countries. Bio-based materials such as wood and bioplastics and plant-based products will be increasingly used as a fuel, feedstock or material	x	x	x	x	x	x	x
C4. Decarbonisation of transport	In this transition there are three important developments: electrification:, zero/low carbon fuels (*most promising are bio-based and synthetic fuels including hydrogen*), modal shift					x	x	x

Source own compilation based on findings Royal Haskoning (2022)

A number of seaports in Europe are stepping up their efforts to become energy and feedstock hubs and growing producers of green hydrogen. Ports are aware it is essential to offer affordable green energy to all players in port areas, at all times, in order to keep the big industry in the region. Both local production and import play a crucial role in this. The first projects related to imports of renewable energy are expected to take shape between 2025 and the end of this decade. Extensive feasibility studies are conducted to analyze ideal sourcing regions, to prepare seaports for receiving the hydrogen carriers of the future, and to set up specific pilot projects in the context of a sustainable economy.

For illustrative purposes, Table 2 in Annex summarizes some of the national policy initiatives in Belgium and the Netherlands to support the development of a green hydrogen economy. Table 3 in Annex provides a summary of the main green hydrogen projects in the Rhine-Scheldt Delta port system, located in the above two countries. The Rhine-Scheldt Delta port system includes all ports located in the estuary systems of the Rhine, Meuse, and Scheldt rivers. In 2021, the port system handled a total cargo volume of about 924 million tons (+5.2% over 2020) and a container throughput of about 30 million TEU (+5%). The two largest ports in Europe, i.e., Rotterdam and Antwerp-Bruges, are located in the Delta, as well as Europe's fourth-largest port (the Amsterdam/Ijmuiden port area along the North Sea Canal) and the tenth-largest port (North Sea Port). It is by far the most important port system in Europe (in volume terms), representing some 27% of all port throughput handled in the EU27 (according to 2021 Eurostat data). The port system is assuming a leadership role, developing into a network of hubs of renewable energy. Although Table 3 in Annex lists large to very large projects, the port industry has also engaged in a lot of smaller initiatives on the production and use of hydrogen. For example, a number of logistics companies are planning to produce green hydrogen on their sites in port areas by using electricity provided by the solar panels on warehouses, or to use hydrogen-powered internal company transport or terminal equipment, linked to mobile hydrogen filling stations.

Overall, the focus on green hydrogen connects different parties and stimulates cross-value chain collaboration in and around seaports. There are many examples of this, such as the PIONEERS[5] and MAGPIE[6] projects, funded by the European Commission, which unite dozens of partners, who work together in addressing the challenges facing European ports, in terms of reducing their environmental impacts. Furthermore, several European seaports have joined various partnerships focused on hydrogen, such as Hydrogen Europe, Clean Hydrogen Alliance and the German H2Global Foundation. The latter foundation has set for itself the goal of making green hydrogen acceptable as an energy substitute in Europe, thereby advancing the energy transition of Europe and its independence from Russian gas. The

[5] PIONEERS builds on the commitment of lighthouse port Port of Antwerp-Bruges to scale up the current state-of-the-art and to demonstrate applicability and feasibility through several demonstrations. The port of Barcelona, Constanta and Venlo are also involved to test these demonstrations, during the project lifecycle.

[6] The MAGPIE project has the ambition to force a breakthrough in the supply and use of green energy carriers in transport to, from and within ports.

International Association of Ports and Harbors (IAPH) joined the Global Ports Hydrogen Coalition in 2021. The coalition is part of the Hydrogen initiative (H2I), originating from the Clean Energy Ministerial (CEM), dedicated to support the scale up of clean hydrogen in the global economy. The program is managed by the International Energy Agency (IEA).

4 Decarbonizing hydrogen production

While a lot of eyes are on green hydrogen, it was mentioned earlier that 96% of current hydrogen production is by means of natural gas. Blue hydrogen is often said to play a role in the transition phase from grey to green hydrogen, although some scholars argue that the greenhouse gas footprint of blue hydrogen production is worse than simply burning natural gas as fuel. This is mainly due to associated fugitive methane emissions (Howarth and Jacobson 2021). A big challenge is therefore how to decarbonize hydrogen production. Using four scenarios (two scenarios where hydrogen could only be produced via electrolysis and two where blue hydrogen from natural gas with CCS was also allowed), Cloete (2020) concluded that blue hydrogen should not be dismissed from the policy agenda, as using hydrogen to integrate higher shares of wind and solar implies considerable costs. For example, when electrolysers are located near the energy users, expensive transmission network expansions are required to transmit wind and solar production peaks to electrolysers. When electrolysers are instead located close to wind or solar power units, large hydrogen transmission and storage capacity is required to handle hydrogen.

Therefore, the focus of port ecosystems as regards hydrogen should not only be on green hydrogen, but also on the decarbonization of grey hydrogen. Blue hydrogen relies strongly on CCUS (Carbon Capture, Utilization and Storage). Although the concept of CCUS is not new, and despite technology developments in the last 50 years, CCUS remains in its early stages of development, considered as an emerging technology. Deployment had stalled in earlier years, and it is only recently that a surge in planned CCUS projects is taking off, towards realizing commercial projects, in Europe and elsewhere. The use of CCUS in general will be essential for CO_2-intensive industries, to achieve net zero emissions, especially in hard-to-abate sectors, with processes inherently generating CO_2 emissions. On the positive side, CCUS projects are taking off. For example, Porthos (Port of Rotterdam CO_2 Transport Hub and Offshore Storage) is developing a project to transport CO_2 from industrial activities in the port, and store it in depleted gas fields beneath the North Sea. Another initiative in the same region of Europe is the Ghent Carbon Hub: an open-access CO_2 storage and liquefaction hub, in the Ghent part of the North Sea Port, currently being studied by Fluxys, ArcelorMittal Belgium and North Sea Port. Commissioning is targeted for 2027. The Ghent Carbon Hub would have a capacity to process six million tons of CO_2 per annum (MTPA), equivalent to around 15% of Belgian industrial CO_2 emissions (press release North Sea Port, 18 August 2022). CCUS will be indispensable in meeting the CO_2 reduction targets in port areas. The emerging cross-border and inter-port cooperation in this area is a positive step to bring its implementation to the next level.

5 Green hydrogen, hydrogen carriers and the changing geography of energy trade

As local green hydrogen production in Europe is not expected to be sufficient to meet demand, hydrogen transport over long-distance will be necessary. Most of the available techniques to do this require the conversion of wind or solar energy to *hydrogen carriers* in or near the exporting port, and the transport of a suitable hydrogen carrier to importing areas. The most commonly considered hydrogen supply chains include (Fig. 1):

- Hydrogen can be transported in *liquid form* (LH_2) at an extremely low temperature in its pure form, but cooling to below -252.87 °C consumes a lot of energy. A wide range of large-scale hydrogen liquefaction methods and approaches exist (see for an overview Aasadnia and Mehrpooya 2018);
- Hydrogen can also be compressed in hydrogen tanks at very high pressures to *compressed hydrogen* (CH_2 *or* CGH_2);
- Hydrogen can be packed in *ammonia* (NH_3). Green ammonia is expected to play a vital role as a hydrogen carrier. Reacting green hydrogen with nitrogen forms green ammonia. This allows hydrogen to be efficiently and safely transported in large volumes. Ammonia synthesis is traditionally achieved via the Haber–Bosch process, converting nitrogen (N_2) to ammonia by a reaction with hydrogen using a metal catalyst under high temperatures and pressures. In recent years, a lot of research has been dedicated to explore sustainable synthesis of ammonia as an alternative to the capital- and often carbon-intensive fossil-fuel-driven Haber–Bosch process (Wang et al. 2021). The ammonia can then be stored and converted again to green hydrogen, but turning ammonia back to hydrogen requires decomposition (cracking) at high temperatures. Green ammonia is immediately usable as CO_2-free fuel, for example in shipping, or as a raw material in the production of fertilizers;
- Hydrogen can be transported by coupling it to other *Liquid Organic Hydrogen Carriers (LOHCs)*. These are organic compounds that can absorb and release hydrogen through chemical reaction. A good example is methyl cyclohexane (MCH) which is a liquid obtained from the chemical reaction of hydrogen and toluene. After the initial hydrogenation step, MCH can be transported by ship, truck or tank wagon. Dehydrogenation ensues, followed either by direct use of the obtained hydrogen, or its conversion back into electricity. The byproduct toluene can be returned to the hydrogenation plant for reuse. Obara (2019) concludes that a hydrogen supply chain based on ammonia has better energy efficiency than one based on MCH.

The above processes lead to various possible green hydrogen value chains. Investigating the technical and economic feasibility of such value chain solutions is crucial for the sustainable development of hydrogen-based energy production and consumption. The search for the cheapest way to produce and transport hydrogen has intensified, entailing key questions such as 'from what distance is it worth

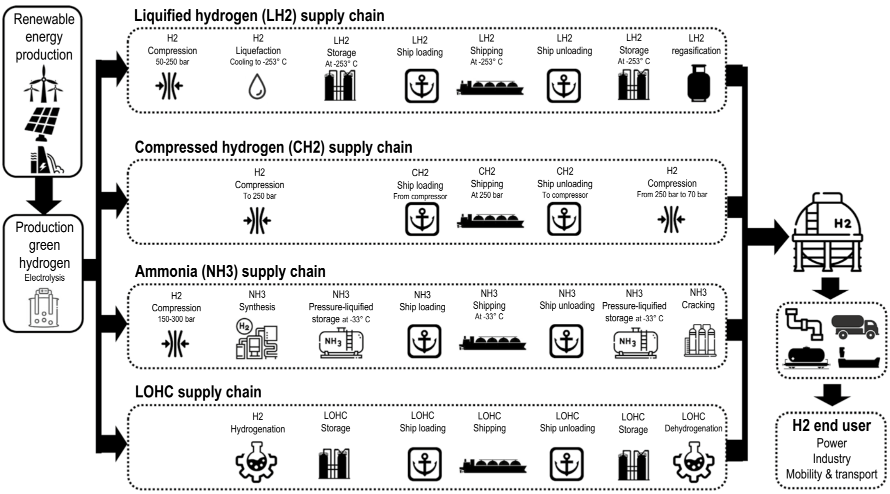

Fig. 1 Most considered supply chain solutions for the import of green hydrogen produced overseas. *Note* The graph assumes H_2 use by the end user. LH_2, CH_2 and ammonia can in many cases also directly serve as input or feedstock for the end user without prior transformation to H_2. *Source* own compilation and adaptation based on Global Energy Ventures (GEV) and HyMove

transporting via ships?', 'when could pipelines be used?' and 'in which form are we going to transport hydrogen?' (i.e., gaseous, liquid, bound with metals (metal hydrides) or carbon) and 'when can we avoid conversion again? (e.g., immediately enter the industry in gaseous form). At present, there is still quite some uncertainty on the preferred hydrogen carrier, regarding rules and regulations, safety standards and certification, and the impact these will have on hydrogen supply chains (for example, safety issues related to ammonia transport near urban areas). In this realm, IRENA (2022c) calls for the alignment of efforts with standards and certification, through common sustainability criteria for traded and supported hydrogen, as well as the alignment of methodologies for hydrogen certification and efforts to set harmonized technical standards.

Although quite a few initiatives for hydrogen export and import facilities have been announced, we are still in the early days of the creation of a global hydrogen carrier, shipping and port network. In the medium term, until the early 2030s, the industry's focus is expected to be on transporting hydrogen in the carriers ammonia, methanol and LOHCs. At a later stage, further technological advances are expected to enable the transport of cooled hydrogen in large volumes in a cost-effective way. Ports are challenged to develop the infrastructure required for each of these hydrogen carriers. The Oxford Institute for Energy Studies (2022a) demonstrates that agreeing on the most appropriate hydrogen carrier will be extremely important, as this will make the entire H_2 value chain more economical and efficient. Although each of these fuels has its own advantages and offers a distinctive set of benefits, none of them is flawless or possesses the characteristics of a perfect hydrogen shipping solution. Technological progress in other decarbonization applications and, most importantly, full commercialization of CCUS solutions, is likely to dramatically change the approach towards long-distance hydrogen transportation.

Irrespective of the chosen technical solution and standards, green hydrogen is likely to influence the geography of energy trade, regionalizing further energy relations, with the emergence of new centers of geopolitical influence, around its production and use. IRENA (2022a) estimates that over 30% of hydrogen could be traded across borders by 2050; a higher share than the natural gas of today. Net energy importers such as Chile, Morocco, and Namibia are emerging as green hydrogen exporters, while fossil fuel exporters, such as Australia, Oman,[7] Saudi Arabia, and the UAE, are increasingly considering green hydrogen to diversify their economies. The P4G-Getting to Zero Coalition Partnership analyzed concrete business opportunities in South Africa[8] (Ricardo & Environmental Defense Fund 2021), Mexico and Indonesia, which could tap into those countries' high renewable energy potential and create an export market for clean hydrogen-derived fuels while creating green jobs (World Economic Forum 2022).

Countries that expect to be importers, such as Japan and Germany, are already deploying dedicated hydrogen diplomacy. In terms of the supply–demand balance, the technical potential for hydrogen production significantly exceeds the estimated global demand. Therefore, realizing the potential of regions like Africa, the Americas, the Middle East, and Oceania could limit the risk of export concentration, but many countries will need technology transfers, infrastructure, and investment at a large scale.

The above developments in the geography of energy trade will obviously impact origin–destination relations of cargo flows handled by seaports. Ports vying for a hub role in the global hydrogen network are urged to align their commercial and marketing efforts with the future geographical shifts in energy flows, and to partner with leading private companies and local, regional and national governments in establishing closer relationships with existing and upcoming countries in the hydrogen economy.

[7] Quite a few European-based companies are engaging in overseas investments in this field. For example, the HYPORT Coordination Company, a joint venture between DEME Concessions and OQ Alternative Energy, acquired a site in Duqm (Oman) to build a green hydrogen plant. This project on a site of 79 ha will have an electrolysis capacity of 500 megawatts. HYPORT signed a second land reservation agreement with the Public Authority for Special Economic Zones and Free Zones (OPAZ) in Duqm. The hydrogen plant in Duqm, a partner port of Port of Antwerp-Bruges in Belgium, will be powered with renewable electricity from wind turbines and solar panels with a combined capacity of 1.3 gigawatts. All of this is located in the renewable energy area of the Special Economic Zone, where HYPORT Duqm was allocated an area of 15,000 ha. A high-voltage transmission line will come from the solar and wind farm to the factory. There, the green electricity is used to produce desalinated water, hydrogen and then converted it into green ammonia. It is stored and shipped from the port of Duqm to Europe and other markets.

[8] For example, Boegoebaai, a proposed deep water port planned for South Africa's Northern Cape province, is set to become an export hub of green hydrogen and sustainable goods from the province. The country's Hydrogen Valley plans to aggregate demand to kickstart hydrogen production and leverage economies of scale. A maritime hub in Durban—Richards Bay aims to bunker and export green hydrogen to the maritime market.

6 The role of ports in making green hydrogen competitive

There is still a considerable production cost difference between green and blue/grey hydrogen. Around 70% of hydrogen production cost is directly related to (renewable) electricity, so the price of electricity determines, to a large extent, the price of green hydrogen. The production of green hydrogen costs between two and three times more than grey or blue hydrogen (IRENA 2022a). In July 2022, for example, green hydrogen cost around 13 euro per kilo in Europe, against 6.50 euro per kilo for blue hydrogen (ING 2022). However, the cost of green hydrogen production is going down thanks to the investments being made, the long-term trend of decreasing costs of wind and solar power and the expected longer-term price increases of fossil fuels. Wood Mackenzie[9] estimates that average green hydrogen production costs will equal fossil fuel-based hydrogen by 2040. In some countries, such as Germany, this will happen by 2030. By 2040, the cost of grey hydrogen is expected to rise by 82%, and that of blue hydrogen, combined with CCS, by 59%, mainly because of rising natural gas prices.

A series of studies by Aurora Energy Research in 2022[10] analyzed the cost of producing hydrogen from electrolysers under four different business models in eight European countries. They conclude that, by 2030, green hydrogen could be produced in some European countries for as little as 3 euro per kg, thus reaching cost parity with blue hydrogen. In order to compete with grey hydrogen, these costs would have to drop to around 2 euro per kg. Germany might have one of the highest production costs and will not reach cost parity with blue hydrogen until the mid-2030s. The country would benefit most from grid-connected electrolysers that can be operated flexibly. In countries such as Norway, Spain and Great Britain, the cheapest way to produce green hydrogen would be to couple an electrolyser with solar and wind energy systems directly on site.

A key factor in bringing green hydrogen costs down, ensuring its availability on a large scale, is *scalability*. In spite of the many renewable energy projects currently underway, or planned, the challenge of hydrogen scalability remains. As mentioned earlier, less than 2% of Europe's energy consumption comes from hydrogen, and this is mainly used for making chemical products like plastics and fertilizers. Moreover, 96% of all hydrogen is produced from natural gas, emitting significant amounts of CO_2 in the process (according to data from the European Commission). Most scenarios do not foresee green hydrogen playing a significant role in Europe before 2030. Mobilizing investments to scale up the production of green hydrogen will require continued efforts towards more international collaboration to shape policy, regional and multilateral agreements and supportive frameworks from regulatory bodies.

The scalability aspect comes with a lot of requirements which can be met more easily by certain locations such as seaport areas (Fig. 2). The following paragraphs elaborate on these key requirements.

9 See https://www.woodmac.com/market-insights/topics/hydrogen-guide/.

10 See https://auroraer.com/category/sector/hydrogen/ for an overview of the findings.

6.1 Locations with available land for hydrogen production and storage infrastructure

The production and storage of green hydrogen requires large surfaces. This challenges ports to make enough land available for production and storage activities which, for many ports, is not an easy task due to land unavailability. Land area is required for electrolysers and related equipment such as transformers, rectifiers, water supply, cooling water towers, separators, dryers and compressors. The overseas import of hydrogen carriers (such as ammonia), requires berths and conversion infrastructure for liquid hydrogen, ammonia and LOHCs (liquid organic hydrogen carriers). Room for energy supply infrastructure, for the cracking of ammonia (conversion to hydrogen) and the recovery of hydrogen from LOHCs is also necessary. Furthermore, one would need storage space for hydrogen carriers and compressor stations, to be able to inject hydrogen in a pipeline system.

6.2 Locations with good maritime and landside connectivity to high capacity electricity grid and to hydrogen infrastructure and assets

Above we discussed the imports of green hydrogen produced elsewhere. The production and storage of green hydrogen in seaports requires a considerable amount of renewable energy and this comes with its own challenges.

First, there is a limited amount of green energy (wind, solar) in Europe. Therefore, some argue that green energy should first and foremost be used for green electricity, i.e., to make current electricity consumption greener (electric cars, water pumps, etc.), and not just as a source for the production of green hydrogen, or the transformation of imported green hydrogen to electricity. IEA (2022b) estimates that Europe will dedicate 7 GW of renewable wind and solar capacity to hydrogen production during the period 2022–2027, encouraged by decarbonisation goals and, more recently, the need to strengthen energy security by substituting Russian gas. Spain is in the lead, accounting for half of Europe's growth, followed by Germany, Sweden, Denmark and the Netherlands.

Second, hydrogen loses a fair amount of energy when produced through electrolysis of wind or solar energy, or when converted back into electricity. Some sources point to losses of up to 60% of the initial wind energy in the 'wind energy to hydrogen back to electricity' cycle.

Third, there are rising concerns in the energy transition drive about the capacity of the electricity grid. In some parts of Europe, high-voltage grid operators can no longer guarantee that new wind turbines, solar parks or power stations can put their power on the grid at all times. Mounting capacity issues in the high-voltage grids are partly the outcome of complex planning and permitting procedures resulting in lengthy trajectories from inception to realization. This can hamper the energy transition efforts. Moreover, the ESG requirements (environmental, social, and governance) imply no shortcuts can be considered in dealing with stakeholders, and with

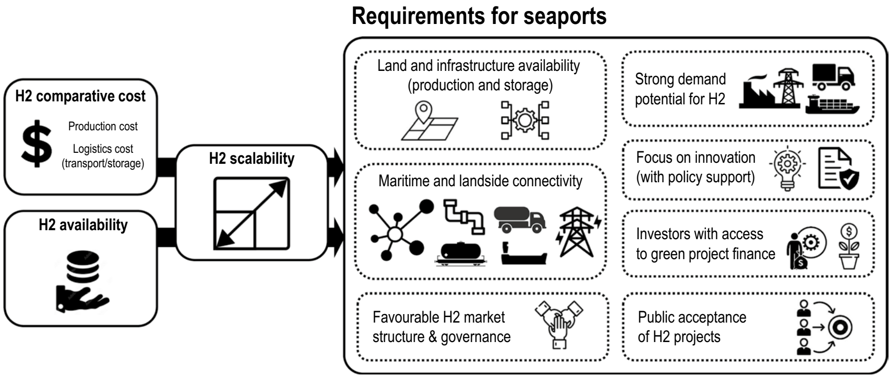

Fig. 2 Key requirements for ports to serve as green hydrogen hubs. *Source* own compilation

the social aspects of large infrastructure projects in the energy sector. As a result, large infrastructure in electric grid networks typically take 10 to 15 years to realize, while actual construction takes only a few years.

Next to the use of wind and solar power, discussions can also arise about the exact use of green hydrogen produced locally or imported. Renewable power generation, mainly by means of solar and wind, requires the availability of a back-up system of conventional power plants. Seasonal energy storage of hydrogen could help to decarbonize dispatchable power through gas turbines or fuel cells. However, the next decade will also see more focus on the use of hydrogen as an industrial feedstock and the decarbonization of high-temperature heat. For example, steelmakers are working on fossil-free steel production methods and hydrogen could play a role in this transition.

6.3 Locations with a strong demand base for green hydrogen

Quite a number of larger seaports have developed into major industrial and logistics ecosystems, and are well connected to other industrial clusters in proximity. This gives them the possibility to help balancing an (understandable) initial enthusiasm with green hydrogen supply, and the emergence of the necessary demand to absorb it. For instance, this could among others be attempted through the prioritization of hard-to-abate industrial applications for hydrogen demand, as well as by promoting hydrogen uptake in logistics (e.g., as a fuel for ships, barges and trucks, directly or through transformation into ammonia or methanol) and industrial applications (e.g., green feedstock/reactant in chemical production, metal treatment, food processing, etc., or as a fuel). Through initiatives that promote green shipping and the use of renewable maritime fuels (see for an overview Iris and Lam 2019; Notteboom et al. 2020), ports can actively contribute to increase the demand for hydrogen and ammonia to help decarbonize shipping. As supply to some extent creates its own demand, the current lack of large-scale green hydrogen production facilities and logistics infrastructure, combined with an intensive capital cost and the associated investment risks, can deter the demand side to step forward and adopt this clean solution. As such, a typical "chicken-and-egg" problem is never far away, with both the supply and demand sides resorting to a 'wait and see' approach, expecting the other party to take the initiative; an issue we further address in our epilogue.

6.4 Locations with a focus on technological innovation and benefiting from strong policy support

The Oxford Institute for Energy Studies (2022b) argues that there are two important key developments that could foster cost reduction in green hydrogen production: technological innovation and policy support measures. In terms of technological progress, the main focus is on minimizing the use of scarce materials for electrolysers, increasing the stack lifetime and system size so that large-scale production can take place, and reducing cold start-up time (solid oxide systems). In terms of policy support mechanisms, direct financial support and fiscal incentives for R&D and production are key at the first stages of market entry and scale-up. Once the technology reaches maturity, and after commercial scale up, there will be a need for strong fiscal incentives, as investors are more likely to be active once a technology reaches critical mass. Apart from electrolysers, supportive policies should also promote renewable electricity and the build-up of infrastructure, as well as demand among end users (e.g. industries and transport).

Innovation is high on the agenda of many seaports (Acciaro et al. 2014; Vanelslander et al. 2019). This includes also innovation in the area of sustainability and energy transition. To drive innovation in the port cluster, port authorities, port industry and branch associations/organisations, private companies and government agencies develop a broad range of local initiatives, such as the setting up of incubators and smart-labs for start-ups and scale ups. Many of such incubators are based on co-creation and co-innovation principles, and the exchange of knowledge among companies. Some port authorities, in cooperation with industry, also contribute in creating a good business environment for universities, R&D focused firms, research centres, consultancy firms and start-ups, to excel in the area of green hydrogen-related research. Often, this is done through partnerships in EU funded projects, the establishment of research chairs and PhD funding, collaboration through hydrogen platforms, etc.

6.5 Locations with access to large-scale project finance which can attract investors and consortia

Large green hydrogen projects demand significant investment, requiring the full spectrum of sustainable finance instruments and technical expertise. Many seaports are home to individual plants or even entire clusters or ecosystems of large energy-related companies. The proximity of these establishments and the existing inter-firm exchanges among them facilitate fostering strong partnerships also in the area of green hydrogen production and distribution. Port authorities from their side understand that such energy-related corporations are essential in making the energy transition in the port area successful.

However, project finance for green hydrogen would only be feasible, making more economic sense, were it to replace grey hydrogen that is already in use in industrial processes. Moreover, this would be particularly the case if there were already hydrogen customers present (e.g., the fertilizer industry or refineries using hydrogen as energy source or feedstock). This way, accruing future cashflows would improve the NPV and IRR outcomes of pre-feasibility studies, limiting the inherent (and often dissuasive) project risk. With emerging innovations, as in our case, this is easier said than done though. Risk here must be assumed through the use of low *social discount rates*. In other words, public administrations should look at the long-run 'economic' rather than 'commercial' ramifications of the investments (Haralambides 1991, 1993a, b, 2019).

6.6 Locations which (can) gain public acceptance for large green hydrogen projects

Over the years, ports have gained a lot of experience in dealing with stakeholders through advances in stakeholder relations management programs and principles (Dooms et al. 2013; Notteboom et al. 2015; Felício et al. 2022). Ports which successfully reach out to civil society and industry stakeholders, towards creating public acceptance of green hydrogen projects have a competitive edge in the green hydrogen economy. Reaching out to stakeholders on the green hydrogen theme concerns not only the provision of information on strategic plans and projects. It also requires efforts to educate the wider population on the sense of urgency in energy transition and the wider ramifications of green hydrogen adoption on emissions, infrastructure and asset needs. Next to information provision, port authorities are also challenged to consider an active participation of certain stakeholder groups in project planning stages, where deemed valuable, or when existing regulations and ESG frameworks and practices require such an involvement.

7 The role of port authorities in the green hydrogen economy

Reaching the end of this editorial, it is useful to elaborate on the role port authorities, or in more generic terms the *managing bodies* of ports, could play in green hydrogen developments and the wider energy transition. One of the factors in Fig. 2 which has not been fully discussed yet, however, regards the creation of a favorable green hydrogen market structure, its governance and regulation. Port authorities have a role to play in this too, in the way they will attempt to facilitate interaction among market players, and define their own role in the green hydrogen economy.

It might be useful at this juncture to say that a port authority (PA) is the entity which, whether in conjunction with other activities or not has, under national law or regulation, the responsibility to manage and administer the port's infrastructures, and co-ordinate and control the activities of the different operators present in the port (Commission of the European Communities 2001; Verhoeven 2010). We particularly focus on the so-called *landlord* port authority which is the most common model of port administration, found in more than 80% of ports around the world. The term 'landlord' derives from the simple fact that the PA, among its many other responsibilities, is the 'curator' and the 'authorized manager' of port land and adjacent aquatic surfaces, to be rented out (leased) for economic profit to the private sector. Often, revenues from this activity amount to 50% of total port revenue (Notteboom and Haralambides 2020; Haralambides 2017).

In the past two decades, a number of scholars have provided more insights to the call for a more active *facilitator* and even *entrepreneurial* role of PAs, also as concerns *sustainability* (Lam and Notteboom 2014; Acciaro et al. 2014; Ashrafi et al. 2020), green supply chain management in ports (Notteboom et al. 2020), the green port concept (Pavlic et al. 2014) and energy transition (Hentschel et al. 2018; Wang and Notteboom 2015). The empirical findings presented so far suggest that PAs can follow very different paths in dealing with current issues in the various areas of port activity (Notteboom and Haralambides 2020). It has also become clear that the achievements and progress made by port authorities in a number of areas under their competence remain rather anemic.

As such, PA-centric approaches to green hydrogen transition (or to energy transition in general) might not be the right choice. For every individual initiative ports might be willing to undertake, PAs and their stakeholders should evaluate whether (a) the port authority may have a statutory role to play and (b) if so, whether such involvement is likely to lead to a superior outcome, compared to a more limited involvement. The PA needs also to decide whether its involvement should be restricted to its statutory domain, or extend beyond the confines of its legal responsibility; what tools or instruments to use (e.g., regulation, penalty or incentive pricing, knowledge development, data sharing, investments, etc.); whether or how to coordinate or form partnerships with other actors; and, finally, whether the PA should act as facilitator or entrepreneur. Thus, the role and function of a PA needs to be contextual: the PA can be an investor/entrepreneur in one area of activity but remain the usual 'onlooker' in another.

Thus, in some cases, (larger) port authorities can consider moving beyond a pure facilitating role and enter into key investments related to energy transition and green hydrogen, particularly in those cases where private investors show reluctance to do so, or when there are possibilities to partner with private or public entities. PAs cannot blindly roll out investments without a cost–benefit analysis included in a convincing business plan. Facilitation of, and investments in, green hydrogen-related projects are often embedded in a port-wide masterplan with its mission, vision and objectives. Stakeholder resistance could arise, however, when a public PA attempts to develop a strong entrepreneurial role in energy transition. Such resistance can manifest itself in the form of rising conflicts with customers and supply chain actors, about commercial investments of the PA which could potentially undermine its presumed market neutrality, or conflicts with local community groups on the correct local input payback.

Large PA investments in green hydrogen-related infrastructure or assets (pipelines, terminals, etc.) can have strong ramifications on PA revenue and cost streams.

For PAs with a landlord function, the financial backbone is currently heavily dependent on port dues (i.e., marine charges and cargo dues) and concession fees. In the medium to long-term, the energy transition away from fossil fuels will negatively affect the revenue streams brought by oil tanker and bulk carrier calls, and fossil fuel-related terminal and industrial activities in the port. Through investments in green hydrogen-related projects, PAs can complement cargo volume dependent revenues (port dues and partly also land fees) with other revenue streams. Thus, targeted investments in energy transition can open the door to new sources of revenue streams which might be less dependent on the vessel and cargo activity level in the port area.

8 Epilogue

Few would today doubt that, in spite of its limited share in meeting energy demand today, *green hydrogen* will be the clean energy source of the future. Suffices to just observe the strides major economies (and their ports) are making to win the leadership in the hydrogen race. Notable among them are the impressive developments in our own port cities of Antwerp and Rotterdam.

In their race towards international energy acclaim, the two ports, as well as other ports in the wider Rhine-Scheldt Delta port system, thanks to their superior infrastructure, natural gas pipelines, institutions and maritime clusters, can be safely expected to play a major role, if sensible preparations and investments are made 'now'. The technological challenges of production, storage and distribution of green hydrogen have already been addressed to a large part, posing few headaches to decision-makers: electrolyser technology is fairly straightforward; (electrolyser) *location choice* decisions can benefit by borrowing from advances in transport and distribution research; distribution infrastructure (pipelines) will become increasingly available thanks to a decline in the demand for natural gas; port terminal facilities will also be freed for new investments due to a decline in the demand for fossil fuel cargo handling (oil and coal); and finally, technology is also there to minimize the carbon footprint of green hydrogen production.

What has not as yet been addressed convincingly though is the *economics of hydrogen*, something we reserve for a forthcoming editorial. The issues are not uncommon in dealing with innovation: Who should assume and manage investment risks? Apparently private investment interest will not materialize, or it will be fairly reluctantly evidenced, if sufficient demand is not present. But demand will only emerge if supply is adequate and at a scale which would ensure competitive pricing. This is the typical *chicken-and-egg* question, requiring a role by the public sector. Here, as it has always been the case with investments in infrastructure, these being the kindle wood of economic development (cf. railroad investments in the US/Canada of the nineteenth century), the role of the public sector is clear: the financing of investments, public or private notwithstanding, ought to be appraised via the usual *social discount rates*; that is, through finance that looks at the long-term economic-, rather than short-term commercial profitability of investments.

Multilateral investment banking is the right vehicle for this. Here, however, new challenges emerge in this regard: can investment finance be somehow *coordinated* among capital providers (e.g., EIB, IBRD, Asian Development Bank, etc.), such that i) wasteful overcapacity is not created (as we have discussed, many countries and their ports have aspirations of becoming energy hubs); ii) the *free-rider* problem, a typical issue in network economics, is limited. Indeed, as we have discussed, mobilizing investments to scale up the production of green hydrogen will require more international collaboration to shape policy, regional and multilateral agreements and supportive frameworks from regulatory bodies. Again, we reserve this discussion for a future article.

We hope this editorial has opened the door to more (port and maritime) green energy research, a new area MEL has prioritized, eagerly soliciting quality contributions.

Annex

See Tables 2 and 3.

Table 2 Key recent policy initiatives affecting green hydrogen adoption in the ports of the Rhine-Scheldt Delta (Belgium and the Netherlands)

Key national policies
The Netherlands: National transport network for hydrogen
In the Summer of 2022, the Dutch Ministry for Climate and Energy presented the final plans for the construction of a national transport network for hydrogen. Gasunie (a natural gas transport and distribution network) will be installing the hydrogen network in the Netherlands and will then also assume the role of its manager. The hydrogen network will connect seaports with the large industrial clusters and with hydrogen storage locations. Connections with Germany (Ruhr area and Hamburg) and Belgium are also being planned. In developing the hydrogen network, existing pipelines are intended to be used, as they become available due to the lower demand for natural gas transport in the coming years. Approximately 85% of the national network will consist of reused natural gas pipelines
Belgium: Hydrogen strategy of the federal government
In late October 2021, the Belgian federal government approved its first hydrogen strategy. On October 12, 2022, the government approved an update of this strategy to reflect the state of its implementation. Additional measures were announced in light of recent developments in the sector. The federal hydrogen strategy aims to use hydrogen and renewable molecules, especially in cases where electrification is not economically viable or technically feasible. This mainly concerns industry and freight transport. The strategy consists of four pillars for which several concrete measures have been identified in which seaports play a key role (FOD Economie 2022): • Pillar 1—Positioning of Belgium as a hub for the import and transit of renewable molecules in Europe • Pillar 2—Strengthening the Belgian leadership in hydrogen technologies • Pillar 3—Creating a robust hydrogen market • Pillar 4—Investing in collaboration for a successful implementation

Table 3 Key recent industry initiatives affecting green hydrogen adoption in the ports of the Rhine-Scheldt Delta (Belgium and the Netherlands)

Key port-related projects and initiatives	
Port of Antwerp-Bruges (Belgium)	
Plug Power	Plug Power intends to build an electrolysis plant for the production of green hydrogen with a capacity of 100 megawatts in the Nextgen district of the Antwerp port area. The facility will produce up to 12,500 tons of liquid and gaseous green hydrogen per year for the European market. The first production of green hydrogen is expected at the end of 2024
Hyoffwind	Partnership between Virya Energy, Parkwind, Eoly Energy and Fluxys to build a power-to-gas installation to convert renewable electricity into green hydrogen. Hyoffwind, will have an electrolyser of 25 megawatts, which can be scaled up to 100 megawatts in the long-run. A Zeebrugge facility will act as an energy hub
MoU with Chile	In November 2021, the ports of Antwerp and Zeebrugge (now port of Antwerp-Bruges) signed a Memorandum of Understanding (MoU) with the government of Chile to set up a corridor to speed up green hydrogen flows between South America and Western Europe. The signing parties will collaborate on a regular basis in order to exchange knowledge, experiences and other information to further strengthen their cooperation
Hydrogen Import Coalition	The Hydrogen Import Coalition includes the port of Antwerp-Bruges, the dredging company Deme, shipping company Exmar, grid operator Fluxys, energy supplier Engie and the Waterstofnet organization. The coalition sustains that Belgium must import renewable energy in the form of hydrogen on a large scale if the country wants to be carbon neutral by 2050. Domestic renewable energy production alone would not be sufficient to achieve this target. Zeebrugge is the designated point to bring the energy ashore. Not only because of the LNG terminal there, but also because a lot of offshore energy comes 'onshore' in the coastal region. The port area of Antwerp comes into the picture as a potential major buyer of this energy because of the energy needs of the petrochemical industry. The Belgian pipeline network is then the connecting link. In the search for locations where the 'renewables' are more easily available and in larger volumes, the role of the affiliated ports of Açu, Cotonou and Duqm is also being examined
H2 Global Foundation	In 2022, the port was part of a first H2 Global Foundation tender for the import of green ammonia, methanol and e-kerosine, thereby kickstarting the first import value chain projects on three key hydrogen carriers

Table 3 (continued)

Key port-related projects and initiatives	
North Sea Port (Belgium/The Netherlands)	
SeaH2Land	Ørsted together with the major industrial companies in the North Sea Port cluster, have presented a vision for a gigawatt-scale project, to reduce carbon emissions in the Dutch-Flemish industrial cluster, via renewable hydrogen. An 1 GW electrolyser and an offshore wind farm will be developed by Ørsted. The electrolyser will link to 2 GW of new offshore wind capacity. ArcelorMittal, Yara, Dow Benelux and Zeeland Refinery support the development of the required regional infrastructure to enable sustainably produced steel, ammonia, ethylene and fuels in the future. About 45 km of regional hydrogen pipelines, between the Netherlands and Belgium, will be developed to exchange hydrogen between the industrial players in the region
Open access hydrogen infrastructure	In May 2022, it was announced that Gasunie, Fluxys and North Sea Port have joined forces to develop the first regional cross-border open-access hydrogen pipeline infrastructure in Europe by 2026
Dow—Yara	Exchange of hydrogen (by-product) via a pipeline between Dow and Yara (completed in 2018)
ELYGator	A project of Air Liquide for 200 MW electrolysis in Terneuzen
H2ero	Development of a 150 MW electrolyser in Vlissingen on-site at Zeeland Refinery (TotalEnergies -Lukoil)
Haddock	Project for a 100 MW electrolyser on-site at Yara Sluiskil with Ørsted
Port of Rotterdam (The Netherlands)	
Holland Hydrogen I	In July 2022, Shell announced the construction start of Holland Hydrogen I, which will be Europe's largest renewable hydrogen plant once operational in 2025. The 200 MW electrolyser will be constructed on the Tweede Maasvlakte terminal and will produce up to 60,000 kg of renewable hydrogen per day. The renewable power for the electrolyser will come from the offshore wind farm Hollandse Kust (noord), which is partly owned by Shell. The renewable hydrogen produced will supply the Shell Energy and Chemicals Park Rotterdam, by way of the HyTransPort pipeline, where it will replace some of the grey hydrogen usage in the refinery
ACE terminal for imported green ammonia	In April 2022, Gasunie, HES International (HES) and Vopak announced their intention to work together to develop an import terminal for green ammonia as a hydrogen carrier. The terminal will operate on the Maasvlakte under the name ACE Terminal, and will be operational as of 2026

Table 3 (continued)

Key port-related projects and initiatives	
OCI	In June 2022, OCI announced the first phase of its ammonia import terminal expansion project in the port of Rotterdam. The investment will increase the throughput capacity from the current c.400 ktpa to up to 1.2 million metric tons per year, with completion expected in 2023. In a later second phase, capacity would increase to above 3 million tons per annum
Port of Amsterdam (The Netherlands)	
Project H2era	Hydrogen company HyCC launched its plans for the construction of *Project H2era*, a 500-megawatt green hydrogen plant at the Port of Amsterdam
Nouryon and Tata Steel	Exploring the construction of a 100 MW hydrogen plant with Nouryon and Tata Steel. This could produce 15,000 tonnes of green hydrogen per year

Source own compilation based on press releases and government and port websites

References

Aasadnia, M., and M. Mehrpooya. 2018. Large-scale liquid hydrogen production methods and approaches: A review. *Applied Energy* 212: 57–83.

Acciaro, M., T. Vanelslander, C. Sys, C. Ferrari, A. Roumboutsos, G. Giuliano, J.S.L. Lam, and S. Kapros. 2014. Environmental sustainability in seaports: A framework for successful innovation. *Maritime Policy & Management* 41: 480–500.

Ashrafi, M., T.R. Walker, G.M. Magnan, M. Adams, and M. Acciaro. 2020. A review of corporate sustainability drivers in maritime ports: A multi-stakeholder perspective. *Maritime Policy & Management* 47 (8): 1027–1044.

Cloete, S. 2020. *Green or Blue Hydrogen: Cost analysis uncovers which is best for the Hydrogen Economy*. Trondheim: Sintef.

Commission of the European Communities. 2001. Reinforcing quality services in Sea Ports—A key for European Transport. COM (2001) 35 Final, Brussels.

Dooms, M., A. Verbeke, and E. Haezendonck. 2013. Stakeholder management and path dependence in large-scale transport infrastructure development: The port of Antwerp case (1960–2010). *Journal of Transport Geography* 27: 14–25.

Felício, J.A., M. Batista, M. Dooms, and V. Caldeirinha. 2022. How do sustainable port practices influence local communities' perceptions of ports? *Maritime Economics & Logistics*. https://doi.org/10.1057/s41278-022-00237-7.

Haralambides, H.E. 1991. Monte Carlo Simulation in risk analysis. *Financial Management*, Vol. 20, No 2, Summer 1991.

Haralambides, H.E. 1993a. Measurement of financial risk in the appraisal of shipping projects. Proceedings of the 6th World Conference on Transport Research. Lyon, France, Elsevier.

Haralambides, H.E. 1993b. Sensitivity analysis of risk in shipping finance. In *Current issues in maritime economics*, ed. Ken Gwilliam. Dordrecht: Kluwer Academic Publishers.

Haralambides, H.E. 2017. Globalization, public sector reform, and the role of ports in international supply chains. *Maritime Economics & Logistics* 19 (1): 1–51.

Haralambides, H.E. 2019. Gigantism in container shipping, ports, and global logistics: A time-lapse into the future. *Maritime Economics & Logistics* 21 (1): 1–60.

Hentschel, M., W. Ketter, and J. Collins. 2018. Renewable energy cooperatives: Facilitating the energy transition at the Port of Rotterdam. *Energy Policy* 121: 61–69.

Howarth, R.W., and M.Z. Jacobson. 2021. How green is blue hydrogen? *Energy Science & Engineering* 9 (10): 1676–1687.

IEA. 2022a. World Energy Outlook 2022a (WEO). International Energy Agency.

IEA. 2022b. Renewables 2022b: Analysis and forecast to 2027. International Energy Agency.

ING. 2022. Edging closer to green hydrogen, https://www.ingwb.com/progress/insights-sustainable-transformation/edging-closer-to-green-hydrogen?li_fat_id=2daf6284-4a2c-4947-8d8c-c4f8a129d8b5.

IRENA. 2022a. Geopolitics of the energy transformation: The hydrogen factor. International Renewable Energy Agency, Abu Dhabi.

IRENA. 2022b. Renewable power generation costs in 2021. International Renewable Energy Agency, Abu Dhabi.

IRENA. 2022c. Accelerating hydrogen deployment in the G7: recommendations for the hydrogen action pact. International Renewable Energy Agency, Abu Dhabi.

Iris, Ç., and J.S.L. Lam. 2019. A review of energy efficiency in ports: Operational strategies, technologies and energy management systems. *Renewable and Sustainable Energy Reviews* 112: 170–182.

Lam, J.S.L., and T. Notteboom. 2014. The greening of ports: A comparison of port management tools used by leading ports in Asia and Europe. *Transport Reviews* 34 (2): 169–189.

Notteboom, T., and H. Haralambides. 2020. Port management and governance in a post-COVID-19 era: Quo vadis? *Maritime Economics & Logistics* 22 (3): 329–352.

Notteboom, T., L.V.D. Lugt, N.V. Saase, S. Sel, and K. Neyens. 2020. The role of seaports in green supply chain management: Initiatives, attitudes, and perspectives in Rotterdam, Antwerp, North Sea Port, and Zeebrugge. *Sustainability* 12 (4): 1688.

Notteboom, T., F. Parola, G. Satta, and L. Penco. 2015. Disclosure as a tool in stakeholder relations management: A longitudinal study on the Port of Rotterdam. *International Journal of Logistics Research and Applications* 18 (3): 228–250.

Obara, S.Y. 2019. Energy and exergy flows of a hydrogen supply chain with truck transportation of ammonia or methyl cyclohexane. *Energy* 174: 848–860.

Oxford Institute for Energy Studies. 2022a. Global trade of hydrogen: what is the best way to transfer hydrogen over long distances?. OIES paper no. ET16, September 2022.

Oxford Institute for Energy Studies. 2022b. Cost-competitive green hydrogen: how to lower the cost of electrolysers. OIES paper no. EL47, January 2022.

Pavlic, B., F. Cepak, B. Sucic, M. Peckaj, and B. Kandus. 2014. Sustainable port infrastructure, practical implementation of the green port concept. *Thermal Science* 18: 935–948.

Ricardo & Environmental Defense Fund. 2021. South Africa: fuelling the future of shipping South Africa's role in the transformation of global shipping through green hydrogen-derived fuels. Study for the P4G Getting to Zero Coalition Partnership.

Royal Haskoning. 2022. The new energy landscape: Impact on and implications for European ports. Study commissioned by ESPO and EFIP, 22 April 2022.

Vanelslander, T., C. Sys, J.S.L. Lam, C. Ferrari, A. Roumboutsos, M. Acciaro, R. Macário, and G. Giuliano. 2019. A serving innovation typology: Mapping port-related innovations. *Transport Reviews* 39 (5): 611–629.

Verhoeven, P. 2010. A review of port authority functions: Towards a renaissance? *Maritime Policy & Management* 37 (3): 247–270.

Wang, S., and T. Notteboom. 2015. The role of port authorities in the development of LNG bunkering facilities in North European ports. *WMU Journal of Maritime Affairs* 14 (1): 61–92.

Wang, M., M.A. Khan, I. Mohsin, J. Wicks, A.H. Ip, K.Z. Sumon, C.T. Dinh, E.H. Sargent, I.D. Gates, and M.G. Kibria. 2021. Can sustainable ammonia synthesis pathways compete with fossil-fuel based Haber-Bosch processes? *Energy & Environmental Science* 14 (5): 2535–2548.

World Economic Forum. 2022. These emerging economies are poised to lead shipping's net-zero transition, press release, 18 August 2022.