Report 2

Study on hydrogen in ports and industrial coastal areas

Recommendations on the areas of priority for R&I projects, safety regulations, codes and standards and non-technical enablers

September 2023

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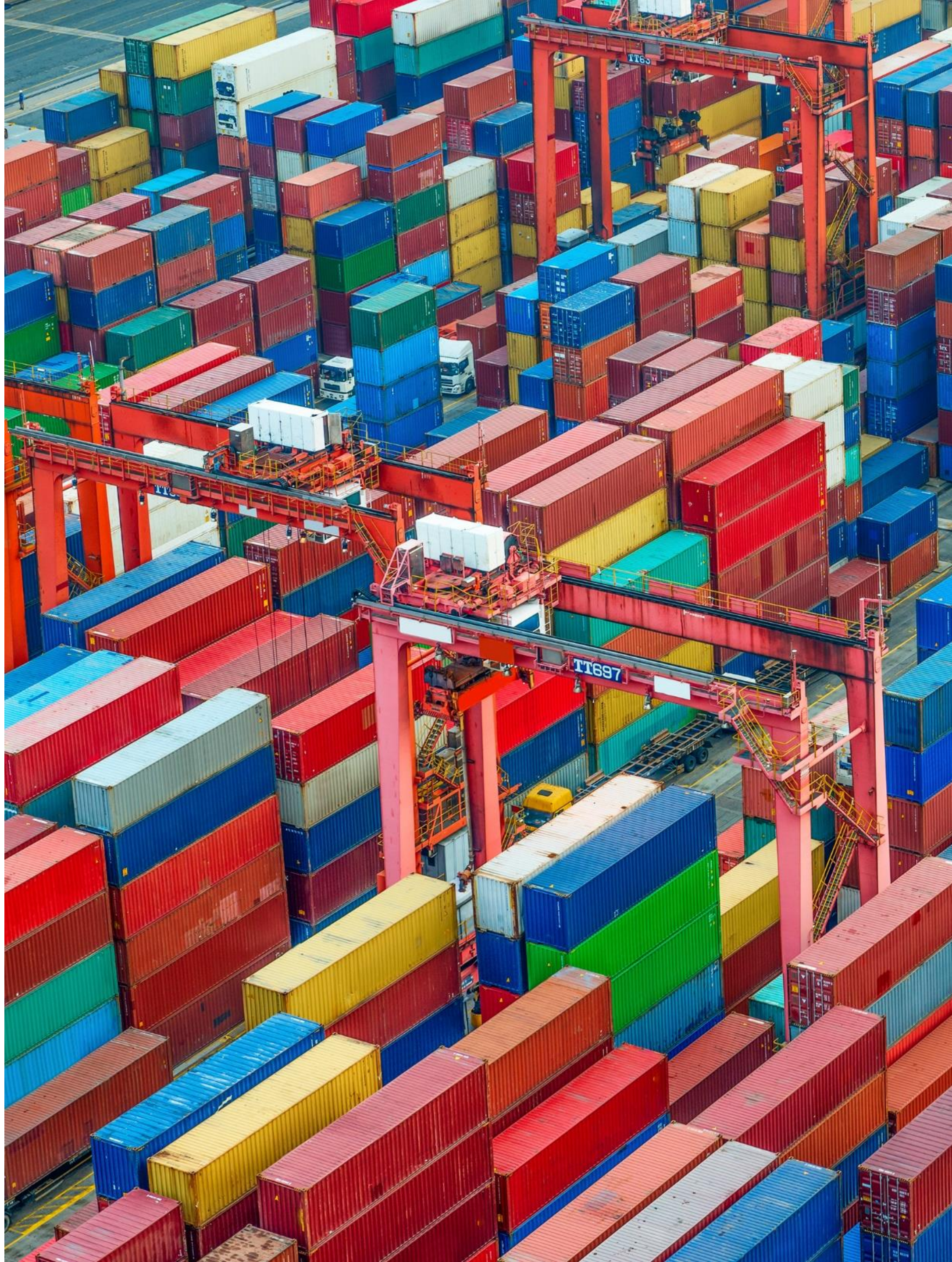

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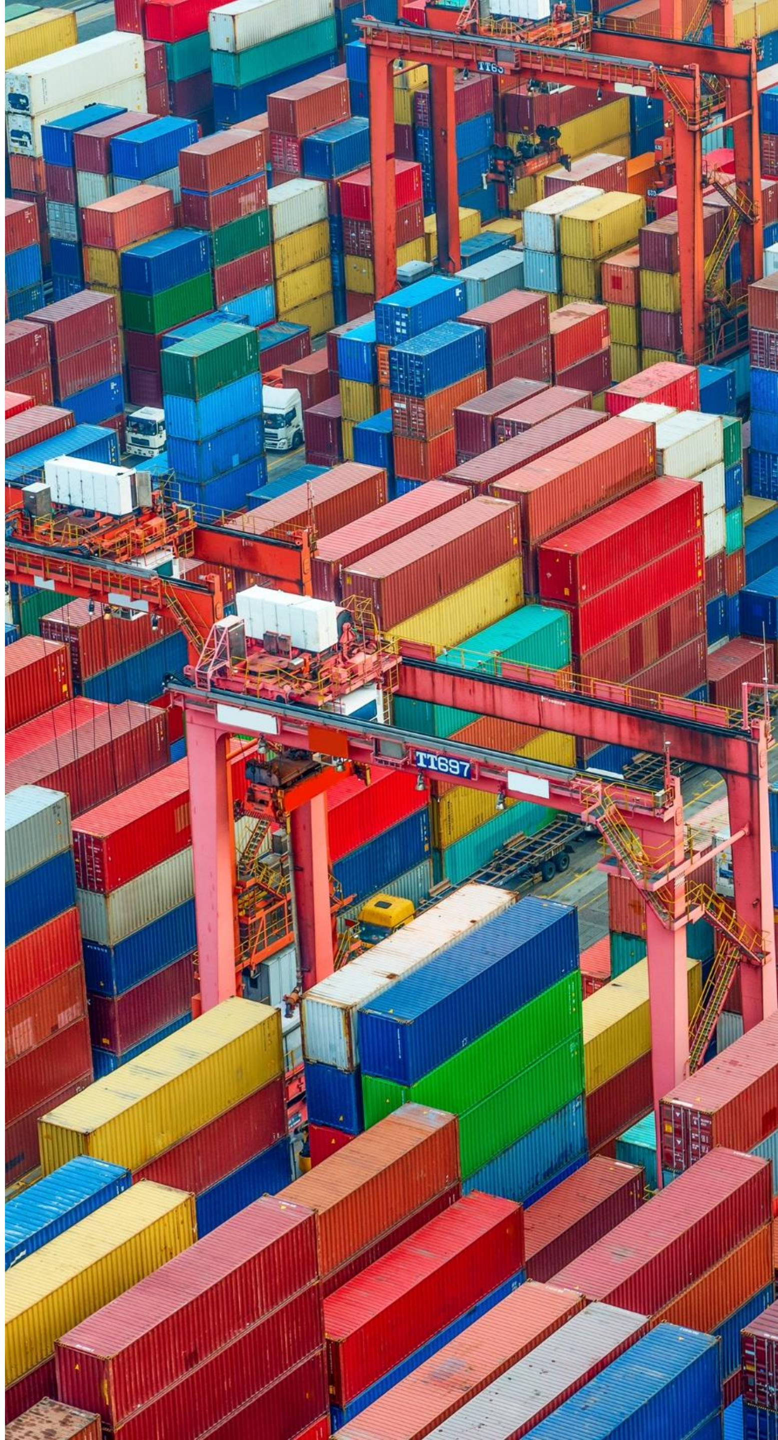

Objectives and tasks of study on hydrogen in ports and industrial coastal areas

Commissioned by

Clean Hydrogen Partnership

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Objectives

Foresight: visibility on the market potential of hydrogen in ports, and a clear roadmap to implement it.

Community building: collaborative resolution of common issues and developing case studies that can act as blueprints to accelerate take-up of financial assistance for hydrogen plans in ports.

Overview of tasks

Task 1	Hydrogen demand and market potential	March 2023
Task 2	Hydrogen supply, storage and distribution	March 2023
Task 3	Definition of business models	March 2023
Task 4	Case studies	November 2023
Report 2		
Task 5	**Recommendations on the areas of priority for R&I projects, safety regulations, codes and standards and non-technical enablers**	September 2023
Task 6	Coalition building	November 2023

The study feeds into the work of the **Global Hydrogen Ports Coalition**, launched at the latest Clean Energy Ministerial (CEM12). This important international initiative brings together ports from around the world to work together on hydrogen technologies.

* Dates refer to delivery date of final reports

Executive summary

With European ports being natural gateways for hydrogen and hydrogen carrier flows, accelerated investment in hydrogen-related infrastructure in port areas is needed to provide decarbonized hydrogen to Europe's industries and transport networks

Driven by the unfolding of the 'Fit for 55' package and the REPowerEU plan, the expected accelerated emergence of a European green hydrogen market will **result in fundamental economic and infrastructure developments** over the next decade and beyond, with **significant impact on maritime and inland port areas.**

Although the expected transformations in ports as a result of the emergence of a European hydrogen economy will be port-specific, **thorough understanding of the implications, requirements, and opportunities of the accelerated emergence of a hydrogen market for port areas will enhance a successful transition, beneficial to all port-related stakeholders.**

Port areas as direct users, provider of infrastructure and transit platform for hydrogen and hydrogen carriers

Port areas as **direct users** of hydrogen and hydrogen carrier fuels	Like other commercial players, climate and energy policies will incentivize **key port stakeholders** (i.e., port authorities, terminal operators, etc.) to set decarbonization targets and **implement decarbonization solutions** for the **assets** and **operations under their purview**. In particular, hydrogen/hydrogen carrier fuels **could play a role** in shifting away from the use of fossil fuels in the following activities: Maritime and inland **shipping**; **Onshore power supply** (cold ironing); **Cargo handling** and **terminal equipment; Industrial activities** located in port areas (e.g., refineries, ammonia plants, other chemicals, etc.) and Refueling of **heavy-duty trucks** (for loading/unloading activities) in port areas.
Port areas as a **provider of infrastructure** for hydrogen and hydrogen carriers	The unfolding of the hydrogen economy will require the construction of **specific infrastructure** to **transmit**, **store**, **convert** and **supply end-users**, which is expected to have a fundamental impact on spatial planning and services within many European ports. In particular, ports may offer a suitable location for the development of the following hydrogen and hydrogen carrier **infrastructure**: New sea or land-based **bunkering**; **Import** terminals; **Landing of offshore** produced **power**; Green hydrogen **production**; **Storage** in tanks; **Conversion** infrastructure; Multimodal hydrogen **refueling** stations.
Port areas as a **transit platform** for hydrogen and hydrogen carriers	European ports, and primarily those located along the **TEN-T** and/or **TEN-E core and comprehensive networks**, can be instrumental in the **transportation** and **supply** of hydrogen and hydrogen carriers. In particular, since ports are often **connected** to nearby **industrial clusters**, **residential areas**, and **energy logistics nodes**, they could serve as a **natural transit hub** for the transport of hydrogen and hydrogen carriers to **multiple end-users** along the **coastal area** and into the **hinterland**. Ports can provide a suitable location for the **transportation** of hydrogen and hydrogen carriers by **pipeline**, **truck trailers**, **trains** and **inland ships** (barges).

The growing demand and supply of hydrogen and hydrogen carriers will likely have far-reaching implications for ports.

- **Space:** Land-use trade-off
- **Facilities:** Service new energy
- **Infrastructure:** Enable new energy
- **Energy flows:** New energy flows
- **Industry:** New technology & clusters
- **Hubs:** Connectivity and alliances

This study aims to inform relevant port-related stakeholders and policy makers on the areas of priority for R&I projects, safety regulations, codes and standards and non-technical enablers for the timely development of hydrogen-related activities and infrastructure in EU port areas

Port areas are expected to be in many ways linked to the development of hydrogen and hydrogen carriers-related activities and infrastructure

In the port

- Import terminals of hydrogen and hydrogen carriers in EU ports
- Bunkering of hydrogen and hydrogen derivatives
- Use of hydrogen and hydrogen-based fuels in the maritime sector
- Use of hydrogen and hydrogen carriers in cold ironing
- Use of hydrogen and hydrogen carriers in port equipment

In the vicinity of the port

- Renewable hydrogen production
- Surface hydrogen and derivatives storage solutions
- Conversion of imported hydrogen carriers into hydrogen
- Multimodal land-based hydrogen refueling stations
- Transport of hydrogen and derivatives from ports to users

In the wider setting of the port area

- Deep sea transport of hydrogen and hydrogen carriers via tankers
- Hydrogen storage in underground geological formations

This study provides a three-level analysis for each of the hydrogen-related activities and infrastructure expected to be developed in port areas

R&I challenges and associated recommendations

Assessment of current **technological challenges,** identification of **areas of priority for R&I** projects and **recommendations on R&I objectives** and millstones (e.g., cost target, research timeline).

Safety challenges and associated recommendations

Identification of **gaps** in **safety regulations, codes** and **standards** and **recommendations** on safety regulations, codes and standards to update or develop.

Non-technical (policy, etc.) challenges and associated recommendations

Identification of **non-technical (policy, regulatory, strategic, etc.) challenges** that are hampering the scale-up of hydrogen-related activities in port and maritime areas and **recommendations** on these non-technical (policy, regulatory, strategic, etc.) challenges.

Prioritization of recommendations to port authorities and other port stakeholders, EU Member States and the EU on R&I challenges for the development of hydrogen and hydrogen carriers-related activities and infrastructure in port areas

Prioritization of recommendations on R&I challenges for the development of hydrogen and hydrogen carriers-related activities and infrastructure in port areas

In the port	
Import terminals of hydrogen in EU ports	🔴
Import terminals of hydrogen carriers in EU ports	⚪
Bunkering of hydrogen and hydrogen derivatives	🟡
Use of hydrogen and hydrogen-based fuels in the maritime sector	🔴
Use of hydrogen and hydrogen carriers in cold ironing	⚪
Use of hydrogen and hydrogen carriers in port equipment	⚪

In the vicinity of the port	
Renewable hydrogen production	🟡
Surface hydrogen storage solutions	🟡
Surface hydrogen derivatives storage solutions	⚪
Conversion of imported hydrogen carriers into hydrogen	🔴
Multimodal land-based hydrogen refueling stations	🟡
Transport of hydrogen and derivatives from ports to users	🟡

In the wider setting of the port area	
Deep sea transport of hydrogen via tankers	🔴
Deep sea transport of hydrogen carriers via tankers	⚪
Hydrogen storage in underground geological formations	⚪

Prioritization of actions :

🔴 High
🟡 Medium
⚪ Low

Note: All specific R&I-related recommendations per step in the value chain of hydrogen and hydrogen derivatives in and near ports and industrial coastal areas are developed in the relevant section in the report.

Prioritization of recommendations to port authorities and other port stakeholders, EU Member States and the EU on safety challenges for the development of hydrogen and hydrogen carriers-related activities and infrastructure in port areas

Prioritization of recommendations on safety challenges for the development of hydrogen and hydrogen carriers-related activities and infrastructure in port areas

In the port	
Import terminals of hydrogen and hydrogen carriers in EU ports	🔴
Bunkering of hydrogen and hydrogen derivatives	🔴
Use of hydrogen and hydrogen-based fuels in the maritime sector	🔴
Use of hydrogen and hydrogen carriers in cold ironing	⚪
Use of hydrogen and hydrogen carriers in port equipment	🟡

In the vicinity of the port	
Renewable hydrogen production	🔴
Surface hydrogen and derivatives storage solutions	⚪
Conversion of imported hydrogen carriers into hydrogen	🟡
Multimodal land-based hydrogen refueling stations	🔴
Transport of hydrogen and derivatives from ports to users	🟡

In the wider setting of the port area	
Deep sea transport of hydrogen and hydrogen carriers via tankers	🟡
Hydrogen storage in underground geological formations	🟡

Prioritization of actions :

🔴 High
🟡 Medium
⚪ Low

⚠ **Note**: All specific safety-related recommendations per step in the value chain of hydrogen and hydrogen derivatives in and near ports and industrial coastal areas are developed in the relevant section in the report.

Prioritization of recommendations to port authorities and other port stakeholders, EU Member States and the EU on non-technical measures (policy, regulatory, strategic) for the development of hydrogen and hydrogen carriers-related activities and infrastructure in port areas

Prioritization of recommendations on **non-technical measures (policy, regulatory, governance, strategic)** for the development of hydrogen and hydrogen carriers-related activities and infrastructure in port areas

- Governance of hydrogen and hydrogen carrier-related activities and infrastructure in port areas 🔴

In the port

- Import terminals of hydrogen and hydrogen carriers in EU ports 🔴
- Bunkering of hydrogen and hydrogen derivatives 🔴
- Use of hydrogen and hydrogen-based fuels in the maritime sector 🔴
- Use of hydrogen and hydrogen carriers in cold ironing ⚪
- Use of hydrogen and hydrogen carriers in port equipment ⚪

In the vicinity of the port

- Renewable hydrogen production 🔴
- Surface hydrogen and derivatives storage solutions 🟡
- Conversion of imported hydrogen carriers into hydrogen 🟡
- Multimodal land-based hydrogen refueling stations 🟡
- Transport of hydrogen and derivatives from ports to users 🟡

In the wider setting of the port area

- Deep sea transport of hydrogen and hydrogen carriers via tankers 🟡
- Hydrogen storage in underground geological formations 🟡

Prioritization of actions :

🔴 High 🟡 Medium ⚪ Low

⚠ **Note**: All specific non-technical recommendations per step in the value chain of hydrogen and hydrogen derivatives in and near ports and industrial coastal areas are developed in the relevant section in the report.

Key recommendations to port authorities and other port stakeholders, EU Member States and the EU on R&I challenges, safety challenges and non-technical measures for the development of hydrogen and hydrogen carriers-related activities and infrastructure in port areas (1/5)

Key recommendations to port authorities and other port stakeholders (1/2)

1 **Port authorities should engage with other relevant port-related stakeholders** (i.e., terminal operators, fuel producers, fuel storage tanks owners, bunkering companies, shipping companies, ship owners, local electricity grid operators, local industrial clusters, etc.) **and systematically assess the societal relevance and the techno-economic rationale for the development of hydrogen and/or hydrogen carriers-related activities and infrastructure** (e.g., import terminal, bunkering, hydrogen production, storage and/or conversion, multi-modal refueling stations, use as a fuel in ships, OPS and port equipment, etc.) **in the port area**.

2 **Port authorities are advised to acquire and maintain a comprehensive understanding of the power and interest of all stakeholders who should be involved in the envisaged hydrogen-related activities in the port area**, with a focus on those stakeholders with a significant degree of influence on the decision-making processes.

3 In those instances where the development of at least one hydrogen or hydrogen carrier related activity is assessed as positive or likely to be positive in the coming years, **port authorities are encouraged to**

- **systematically consider setting up a hydrogen working group composed of representatives of local authorities as well as private stakeholders operating in the port ecosystem** (e.g., local industries, gas network operator, storage infrastructure providers, shipping companies, road transport companies, etc.), and,
- **develop a clear roadmap** with key **milestones**, **conditions**, and **organizational structure** for the successful and safe integration of one or more hydrogen and/or hydrogen-related activities in the port area.

4 **Port authorities are recommended to engage with the competent regulatory authorities** in their respective jurisdictions to **articulate a clear regulatory framework for land use management in port areas** that establishes a **transparent division of responsibilities** among relevant entities for the deployment of hydrogen and hydrogen carriers-related activities within a given port area.

5 In an effort to develop a more integrated approach to coastal energy planning, **coalitions or framework agreements should be developed between port authorities, key other relevant port-related stakeholders** (e.g., shipping companies, vessels-owners, fuel producers and local industrial end-users), **and neighboring connecting ports** (i.e., green corridors approach).

6 In those Member States that have clearly articulated in their energy policy framework their ambition to import hydrogen or hydrogen carriers from outside the EU, **port authorities could assist their national governments and the European Commission in establishing strong and resilient bilateral and/or multilateral strategic partnerships with future hydrogen and hydrogen carrier exporting countries**.

7 Pending the development of IMO and ISO technical regulatory standards, **relevant stakeholders (e.g., classification societies)** could align themselves to **establish one harmonized risk-based "alternative design" approval procedure, guidelines** and **checklists** for the development and operation of **alternative maritime fuel bunkering infrastructure and equipment** used in Member States, **ships powered by hydrogen and hydrogen-based fuels** and new **ship tankers for maritime hydrogen transport**.

Key recommendations to port authorities and other port stakeholders, EU Member States and the EU on R&I challenges, safety challenges and non-technical measures for the development of hydrogen and hydrogen carriers-related activities and infrastructure in port areas (2/5)

Key recommendations to port authorities and other port stakeholders (2/2)

8 **Port authorities should co-invest in specific flagship demonstration projects** to demonstrate the technical and economic feasibility of, for example, the safe use of hydrogen (e.g., in fuel cells) in tugboats, barges, port vessels, cargo handling and other terminal equipment and cold ironing machinery owned by port authorities and other port operators.

9 Should the **port authorities not have direct responsibility for the development and/or operation of hydrogen and/or hydrogen carrier-related activities and infrastructure** (including end-uses), they are encouraged to **actively contribute to stimulating**, or **compelling** (depending on the port's governance and regulatory powers) **relevant port-related stakeholders to timely develop and/or operate hydrogen (carrier)-related activities and infrastructure** (including end-uses). For instance, this incentivization could be done by:

- **Altering existing port-related regulatory regimes**, **providing guidance** (i.e., in coordination with relevant maritime associations), or **including specific provisions in tender specifications or terminal concession contracts** (e.g., to allow vessels powered by hydrogen and hydrogen-based fuels to call at the port's berth; to require terminal operators to decarbonize their cargo handling equipment by 2030, etc.).
- **Incentivizing calls by hydrogen and hydrogen-based-fueled ships** (e.g., by reducing port fees and fuel taxes, granting privileged access to certain docks or time slots, etc.).
- **Providing support to identify and secure access to European and/or national public funding programmes** that could be tapped into for the completion of such hydrogen-related projects.
- **Identifying land areas in the vicinity of the port that would be suitable for the construction and operation of hydrogen or hydrogen carriers-related infrastructure** (e.g., production, import, storage, conversion, transport, refueling and end-use).
- **Providing training support for personnel of port-related stakeholders** (e.g., terminal and bunkering operators) on the safe handling, operation, maintenance and/or use of new infrastructure and/or equipment dealing with hydrogen or hydrogen carriers.
- **Bringing together relevant public and private stakeholders** (e.g., fuel producers with bunkering operators and ship owners; owners of fuel storage facilities with transport operators and local industries or hinterland end-users, etc.) **for facilitating the development of hydrogen-related projects** in the vicinity of ports.
- **Facilitating joint agreements with potential end-users** (e.g., shipping and road freight companies), whereby, as demand for hydrogen or hydrogen-based fuels increases, the port will guarantee the provision of the appropriate fuel(s) and refueling infrastructure (e.g., bunkering, multimodal refueling stations) at the port premises.
- **Ensuring the availability of basic operational utilities and services** (e.g., road access, maintenance, piping, cabling, etc.) necessary for the safe and efficient construction and operation of hydrogen or hydrogen carrier related infrastructure (including end use).
- **Encouraging the relocation of companies that are expected to participate in the hydrogen economy**, either as manufacturers of hydrogen consuming assets (e.g., new generations of vessels) or as end-users of hydrogen (e.g., primary steel, ammonia or chemical producers), closer to the port.
- **Promoting social and public acceptance of hydrogen and hydrogen carriers** (e.g., ammonia) handling, utilization and/or transport among local stakeholders.

Key recommendations to port authorities and other port stakeholders, EU Member States and the EU on R&I challenges, safety challenges and non-technical measures for the development of hydrogen and hydrogen carriers-related activities and infrastructure in port areas (3/5)

Key recommendations to EU Member States (national governments)

① **Member States should consider including specific provisions** (e.g., short-, medium- and long-term timelines and quantitative milestones, required infrastructure, investment needs, etc.) **in their respective national hydrogen strategy for the timely development of integrated hydrogen-related infrastructure along coastal areas under national jurisdiction**. When defining the need for hydrogen-related infrastructure in port areas, **national hydrogen strategies should consider spatial integration** of hydrogen infrastructure, **local zoning, specific environmental regulations (including permitting procedures)** and **public and local community acceptance**.

② In the framework of their national hydrogen strategy, **Member States are encouraged to promote and facilitate greater regional coordination, integration and mutualization** (at the level of coastal areas) for the development of hydrogen-related activities and infrastructure (e.g., storage and distribution). To this end, **Member States could work towards the development of integrated cross-border hydrogen valleys involving several maritime and inland ports**.

③ **National policies and funding programs** that aim at accelerating the decarbonization of the shipping sector and the import of hydrogen and hydrogen carrier to the EU **should be tailored to support the design, construction and retrofitting of zero-emission ships**, **hydrogen and hydrogen carrier tankers and associated maritime equipment by EU companies over non-EU companies**.

④ In areas where social and public acceptance concerns are likely to interfere with the foreseen increase in hydrogen and hydrogen carriers-related activities, **strategies and associated actions** (e.g., by involving local communities in project development) **should be defined to minimize social and public opposition to the development of relevant infrastructure**.

⑤ **Member States are advised to allocate direct public funding to pioneers in the EU port areas that are launching investments in R&I and market-ready projects aiming at demonstrating or decreasing the cost** of **import** (e.g., large-scale LH2 terminal), **production** (e.g., large-scale offshore electrolyzer facilities), **storage** (large-scale LH2 and GH2 storage in tanks and underground storage facilities), **conversion** (e.g., ammonia cracking and LOHC dehydrogenation), **transport** (ocean-going LH2 tankers, truck trailers for GH2 transport), **refueling** (bunkering, compression at HRS) and **end-use** (e.g., engines and fuel-cells for deep-sea, short-sea and port vessels, tugboats, urban ferries, dredging ships, barges, cargo handling and other heavy-duty port equipment, cold ironing machinery) **of LH2, GH2, ammonia and LOHC in a port environment.**

⑥ All **LNG terminals and large-scale storage tanks** currently under construction or planed **should be designed considering later conversion to LH2 or hydrogen carriers** (e.g., ammonia).

⑦ **Member States are encouraged to design an appropriate policy and regulatory framework to enable the effective, rapid and large-scale uptake of renewable hydrogen production activities in port areas**. This includes:

- The establishment of **national environmental, planning and safety legislation** (e.g., permitting procedure, safety standards, spatial integration requirements) for the design and operation of electrolysis installations in port areas.
- The **classification of power cables connecting onshore or offshore renewable electricity generation facilities and electrolysers** in national electricity legal regimes and the **adoption of provisions on the ownership and operation of such cables**.
- **Addressing the growing concern over the lack of availability of freshwater supplies** needed by electrolysis facilities.

Key recommendations to port authorities and other port stakeholders, EU Member States and the EU on R&I challenges, safety challenges and non-technical measures for the development of hydrogen and hydrogen carriers-related activities and infrastructure in port areas (4/5)

Key recommendations to the European Union (1/2)

1. Complementary to national funding programs, **the EU could consider to allocate public funding** (e.g., through CEF-Energy, IPCEI, Horizon Europe, Clean Hydrogen Partnership, ZEWT Partnership, etc.) **to pioneers in the EU port areas that are launching investments in R&I and market-ready projects aiming at demonstrating or decreasing the cost** of **import** (e.g., large-scale LH2 terminal), **production** (e.g., large-scale offshore electrolyzer facilities), **storage** (large-scale LH2 and GH2 storage in tanks and underground storage facilities), **conversion** (e.g., ammonia cracking and LOHC dehydrogenation), **transport** (ocean-going LH2 tankers, truck trailers for GH2 transport), **refueling** (bunkering, compression at HRS) and **end-use** (e.g., engines and fuel-cells for deep-sea, short-sea and port vessels, tugboats, urban ferries, dredging ships, barges, cargo handling and other heavy-duty port equipment, cold ironing machinery) **of LH2, GH2, ammonia and LOHC in a port environment.**

2. **EU policies and funding programs** that aim at accelerating the decarbonization of the shipping sector and the import of hydrogen and hydrogen carrier to the EU **should be tailored to support the design, construction and retrofitting** of zero-emission **ships**, hydrogen and hydrogen carrier **tankers and** associated **maritime equipment** by EU companies over non-EU companies.

3. **The EU is encouraged to provide financial support for conducting a comprehensive study** that will clarify whether (and if so, under what specific conditions) it is **technically and economically feasible to convert existing LNG terminals into LH2, ammonia and LOHC terminals**.

4. **The EU** (through its most active/influential Member States) **should encourage the IMO to develop prescriptive harmonized international regulations as well as technical and safety standards** for the **sea-based transportation** of hydrogen, **import terminals of hydrogen and LOHC**, the **bunkering** of hydrogen and hydrogen-based fuels and the **utilization** of hydrogen and hydrogen-based fuels **in deep-see and short-sea applications**. In particular, the IMO IGC Code, IGF Code, ISM Code and the MARPOL Convention (i.e., NOx Technical Code) should be revised.

5. The **EU should encourage the ISO** to
   - **Align existing ISO standards with the changes to the IMO codes** recommended in the *recommendation 4*;
   - **Develop** new **standards** and **protocols** for **vehicle on-board hydrogen storage** (GH2, LH2, ammonia, LOHC) and the safe integration of on-board storage and hydrogen propulsion systems;
   - **Include LOHC in ISO 15916** (consideration for the safety of hydrogen systems);
   - **Adapt the current standards on LNG to liquified hydrogen and compressed/refrigerated ammonia**.
   - **Develop guidelines for maritime bulk storage of hydrogen carriers** covering both existing and new terminals, including conversion services (liquefaction, (de)hydrogenation, purification).
   - **Develop a technical standard for tank** volume, tank typology, tank farm lay-out and tank pressure (when applicable) in relation to external safety/safety distances, considering the SEVESO III guideline.
   - **Develop standards and protocols for port equipment heavy duty vehicles** and **short distance maritime operations**.
   - **Develop standards and protocols for compressed hydrogen refueling points** for **maritime and inland vessels**.

Key recommendations to port authorities and other port stakeholders, EU Member States and the EU on R&I challenges, safety challenges and non-technical measures for the development of hydrogen and hydrogen carriers-related activities and infrastructure in port areas (5/5)

Key recommendations to the European Union (2/2)

6 Building on future updated IMO regulatory framework (see above), **the EU is advised to work with** the relevant regulatory and standardization authorities (e.g., **CCNR** and **CESNI) to develop prescriptive harmonized EU-wide regulations, clear guidelines to Member States on administrative practices and permitting procedures**, **as well as technical and safety standards** for the **transportation of hydrogen on inland waterway vessels**, the **bunkering** of hydrogen/hydrogen-based fuels **in inland ports**, the **utilization** of hydrogen/ hydrogen-based fuels **in inland waterway ships** and **hydrogen-based cold ironing systems**

7 **The EU is advised to work with** the relevant standardization authorities (e.g., **CEN** and **CENELEC**) **to develop prescriptive harmonized EU-wide regulations, clear guidelines to Member States on administrative practices and permitting procedures, as well as technical, operational and safety standards** for 1) the **construction** and **operation** of **multi-modal stationary hydrogen refueling stations** in port areas, **cargo handling** and **other terminal equipment** powered by hydrogen/hydrogen-based fuels and **hydrogen carrier conversion facilities** (ammonia crackers, LOHC dehydrogenation), 2) **the transportation of gaseous and LH2 by rail** in the EU and 3) the **large-scale inherently safe production of hydrogen**.

8 **The EU should consider revising the relevant regulatory provisions in the Seveso Directive** so that the **fairly low threshold for on-site hydrogen storage** (5,000 kg maximum) does not apply to port authorities, terminal operators or other third parties willing to initiate the use of hydrogen as an energy source in cold ironing activities.

9 The **EU should support the development of testing and certification protocols** for

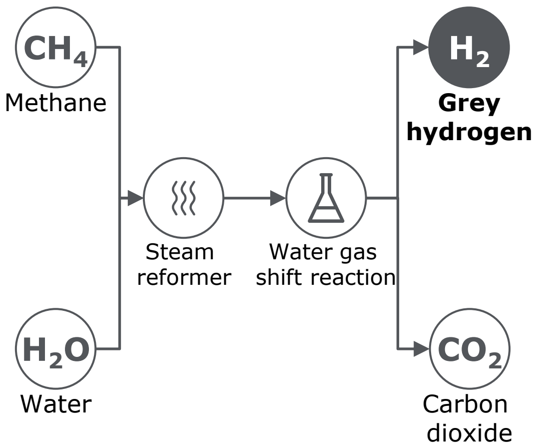
- Materials exposed to the various hydrogen carriers and materials in direct contact (and experiencing frequent temperature swings) with LH2.
- Inland navigating vessels using hydrogen/hydrogen carriers as fuel.
- Swapping empty fuel tanks while the cold ironing system is in service.
- First responders in case of a calamity (use of hydrogen in cold ironing)
- LH2 and GH2 storage tanks.
- The performance, failure rates and durability of membranes (large-scale offshore electrolyzer technologies)
- The detection of in-building flammable atmospheres in facilities housing electrolyzer stacks.
- Unified hydrogen refueling connections, testing and verification.
- The safe mooring of sea going vessels within a harbor environment in light of the required safety distances around the ships due to boil-off.
- Steels resistant to hydrogen embrittlement.
- Wellbores to be used for hydrogen storage in existing gas storage facilities.

Context

Hydrogen as an energy career is expected to play a key role in decarbonizing activities where other alternatives might be unfeasible or more expensive

There are two dominant types of hydrogen for decarbonization: **"green" hydrogen** (also called **renewable hydrogen**), which is obtained via electrolysis using renewable electricity to split water into hydrogen and oxygen, and **"blue" hydrogen** (also called **low-carbon hydrogen**), which is produced in methane reforming plants equipped with CO_2 capture units and subsequent CO_2 storage[1].

Grey hydrogen



CH_4 Methane

H_2O Water

Steam reformer

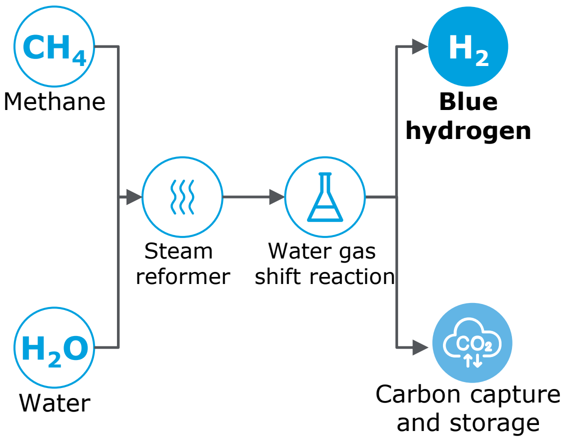
Water gas shift reaction

H_2 **Grey hydrogen**

CO_2 Carbon dioxide

- Current hydrogen production in Europe is almost exclusively **grey hydrogen** from natural gas.
- The production of grey hydrogen is **highly carbon intensive**.

Blue hydrogen



CH_4 Methane

H_2O Water

Steam reformer

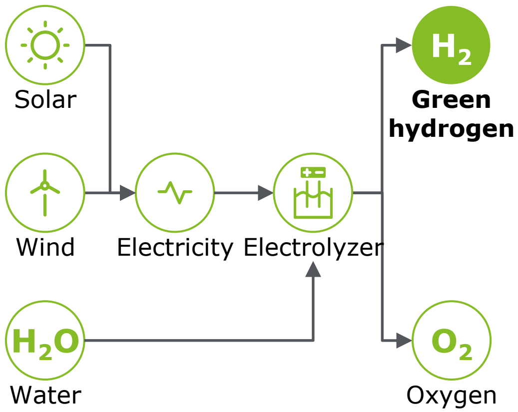
Water gas shift reaction

H_2 **Blue hydrogen**

CO_2 Carbon capture and storage

- Blue hydrogen has the **same production method** as grey hydrogen but uses **carbon capture and storage (sequestration).**
- It has **controllable production capacity** hence does not require storage.
- Blue hydrogen production in the EU is dependent on the EU's supply of natural gas.

Green hydrogen



Solar

Wind

Electricity

Electrolyzer

H_2O Water

H_2 **Green hydrogen**

O_2 Oxygen

- Green hydrogen is the only **100% renewable hydrogen** production method.
- It requires **storage** to balance out **fluctuating production** from intermittent renewable energy sources with constant demand.
- Electrolysis **technologies vary**; mature **alkaline** technology is best for **stable electricity** supply, newly developed **PEM** technology for **intermittent** supply.

Note: (1) Even though not in the scope of this study, other hydrogen production processes such as "pink hydrogen' (produced from nuclear-based electricity) and "turquoise" (methane pyrolysis) could also play a role depending on policy, technological and economical evolutions.

Accelerated investment in hydrogen-related infrastructure in port areas is needed to provide decarbonized hydrogen to industrial and transport end-users

Hydrogen, especially of renewable origin (i.e., green hydrogen), has been consolidating its position in the **EU's energy transition policies and envisaged trajectories**, ever since the publication of the **European Green Deal**, followed by the **Hydrogen Strategy for a climate-neutral Europe**, and the **'Fit for 55' package**, and culminating with the **Hydrogen Accelerator in the REPowerEU plan** from May 2022[1].

To achieve the highly ambitious REPowerEU targets …

20 Mt of renewable hydrogen consumed in the EU by 2030

10 Mt produced domestically (in the EU)

10 Mt imported from non-EU countries

… large public and private capitals are required[2]…

EUR 200-300 billion for **additional renewable electricity production** (500-550 TWh).

EUR 50-75 billion for **electrolysers** (120 GW of capacity).

EUR 6-11 billion for **storage infrastructure**.

EUR 28-38 billion for **EU-internal pipelines.**

Total investment costs to meet **2030 renewable hydrogen ambitions** are expected to be in the range of **EUR 335-471 billion**

… for the development of *necessary* port infrastructure

> *"The consumption of 20 million tonnes of renewable hydrogen will also require accelerated investments in hydrogen infrastructure to bring renewable hydrogen production in areas with high renewable energy resources to the end-consumers.* ***The development of port infrastructure and their connection to both industrial and transport users in the vicinity will be of critical importance****. Therefore, the Commission considers as crucial* ***support for the development of necessary port infrastructure to receive imports of hydrogen****, including in the form of renewable ammonia and other renewable hydrogen by-products"*
>
> **REPowerEU Plan**
> *Staff Working Document: Investment needs, hydrogen accelerator and bio-methane plan* - SWD(2022) 230 final

Notes: (1) Although other hydrogen production processes (i.e., hydrogen obtained via electrolysis using nuclear electricity or hydrogen obtained from reforming of methane with CO_2 capture and storage) could also play a role depending on policy, technological and economical evolutions, the EU has consistently outlined that institutional efforts for the development of a hydrogen economy by 2030 and beyond will be geared towards renewable (green) hydrogen, the focus of this study; (2) Staff Working Document: Investment needs, hydrogen accelerator and bio-methane plan (SWD(2022) 230 final)

A rapidly evolving EU policy context and legal framework creating momentum for the development of hydrogen activities in European ports areas

Hydrogen Energy Network (HyENet), informal platform composed of representatives from Member States energy ministries that aims to help national authorities to develop hydrogen projects.

EU Strategy on Energy System Integration, laying down the perspectives for hydrogen as an energy carrier for decarbonizing hard to abate sectors and providing long-term storage and buffering capability.

A hydrogen strategy for a climate-neutral Europe, putting forward a vision for the creation of a European hydrogen ecosystem from R&I to scale up production and infrastructure to an international dimension.

European Clean Hydrogen Alliance, gathering stakeholders covering the entire hydrogen value chain (6 working groups) with the view to steer the development of hydrogen-related activities and infrastructure in the EU.

Sustainable and Smart Mobility Strategy, providing clarifications on the potential for hydrogen to play a significant role in decarbonizing the transport sector wherever electrification is not viable, stating the significant potential that inland and seaports have to become new hydrogen hubs, laying down the target of zero-emission marine vessels being market-ready by 2030, stating the need of boosting the of renewable fuels in the maritime sector and emphasizing on the creation of zero-emission ports.

Offshore Renewable Energy Strategy, stating that large-scale development of offshore wind would enable decarbonization of hard-to-abate sectors by converting electricity in renewable hydrogen

EU Industrial Strategy, providing clarifications on the potential for hydrogen to play a significant role in decarbonizing EU industries

Clean Hydrogen Mission, international partnership with the objective to reduce end-to-end costs to USD 2 per kilogram by 2030 by increasing research and development in hydrogen technologies and industrial processes

(Recast) Trans European Network for Energy (TEN-E) Regulation, including hydrogen transport infrastructure and certain types of electrolysers in the scope of the Regulation and laying down the down rules for the timely development and interoperability of trans-European hydrogen networks

The NAIADES III action plan for inland ports, aiming to boost the role of inland waterway transport in mobility and logistics systems notably by shifting more cargo to Europe's rivers and canals and facilitate the transition to zero-emission barges by 2050.

⬜ EU policy document and initiative

🟦 EU legislation

A rapidly evolving EU policy context and legal framework creating momentum for the development of hydrogen activities in European ports areas

★ **(Recast) Trans European Network for Transport (TEN-T) Regulation**, requiring, across the TEN-T network, the deployment of the charging and refueling infrastructure needed for alternative transport fuels in line with AFIR.

(Recast) Alternative Fuels Infrastructure Regulation, stating that publicly accessible hydrogen refueling stations should be deployed along the TEN-T core and the TEN-T comprehensive network as well as in all urban node[1].

Clean Hydrogen Partnership, composed of the European Commission, fuel cell and hydrogen industries represented by Hydrogen Europe and the research community represented by Hydrogen Europe Research, it aims at strengthening and integrating EU scientific capacity on green hydrogen (budget: €1 billion euro for the period 2021-2027, complemented by at least an equivalent amount of private investment).

★ **(Recast) Regulation on the internal market for renewable and natural gases and hydrogen**, creating an EU legislative framework for hydrogen networks, comparable to those that already exist for natural gas and electricity; proposing to create a European Network of Network Operators for Hydrogen (ENNOH) to define a non-binding Union-wide ten-year network development plan for hydrogen, and stating that a maximum of 5% blending of hydrogen in natural gas networks is possible.

2021 **(continued)**

(Recast) Renewable Energy Directive (RED II & III), defining the concept of RFNBOs in transport (RED II) and other end-use sectors (RED III) and the rules for RFNBOs to account towards RES targets; setting demand-side mandatory targets in industrial and transport sectors[2].

(Recast) EU Emissions Trading Scheme Directive, stating that from 2023 the shipping industry will be gradually added to the scheme. This affects ships within the EU as well as ships calling at a port in the EU. trains/trucks/cars etc.

ReFuelEU Aviation Initiative, requiring EU airport to progressively switch to "synthetic aviation fuels" (e-kerosene) in the fuel supplied to operators[3].

FuelEU Maritime Initiative, requiring ships carrying EU trade to progressively switch to sustainable fuels and use onshore power supply when available[4].

(Recast) CO2 Standard for new cars and vans, requiring that 100% of the cars and vans put on the market from 2035 are emissions-free, including fuel-cell and other hydrogen-powered vehicles.

★ **(Recast) Energy Taxation Directive (ETD)**, granting the lowest minimum tax rate of €0.15/GJ to RFNBOs and no longer fully exempting fuels used for intra-EU maritime transport from energy taxation.

⬜ EU policy document and initiative 🟦 EU legislation ★ EU legislation still under debate (as of 07/2023)

Notes: (1) In March 2023, EU institutions reached a deal on the Alternative Fuels Infrastructure Regulation (AFIR), the key piece of legislation for Europe's nascent hydrogen-powered road transport sector. Article 6 of the regulation will mandate the construction of one gaseous hydrogen refueling station (HRS) every 200 km on the TEN-T core network by the end of 2030, as well as one HRS in every urban node. The stations will have a daily supply capacity of one ton of hydrogen for all modes of road transport. Member States must prepare an HRS deployment plan by 2027 that will satisfy the needs of hydrogen powered road mobility; (2) In March 2023, the European Parliament, Council and Commission reached a final agreement on the review of RED III. Key provisions related to hydrogen are the following: 1) Industry must procure at least 42% of its hydrogen from RFNBOS by 2030, though countries that can achieve a fossil-free hydrogen mix of at least 77% by 2030 can see that target reduced by 20%; 2) In transport, fuel suppliers must achieve either a 14.5% reduction in greenhouse gas (GHG) emissions associated with their fuels or achieve at least a 29% renewables share in the fuel supply. In addition, at least 5.5% of the fuel mix must be composed of advanced biofuels and RFNBOs (combined binding target). Fuel suppliers will be free to choose their preferred fuel, but they must guarantee at least 1% is sourced from RFNBOs – which will lead to approximately one million tons of RFNBO demand (for more information, see here); (3) In April 2023, co-legislators reached a final agreement on the ReFuelEU Aviation regulation, which aims to promote the production and up-take of sustainable aviation fuels (SAFs) until 2050. SAFs are now set to make up 70% of all fuels supplied to operators at EU airports by 2050. Also, a specific proportion of the fuel mix (1.2% in 2030, 2% in 2032, 5% in 2035 and progressively reaching 35% in 2050) must comprise synthetic fuels like e-kerosene (more information here). (4) In March 2023, the European Parliament and the Council reached an agreement on the FuelEU Maritime regulation to reduce the carbon footprint of Europe's maritime sector, including GHG reduction targets, a 2% target by 2034 for RFNBO uptake in the sector and a 2x multiplier until 2035 (allowing every ton of e-fuel used to be counted twice towards GHG savings) – for more information, see here.

A rapidly evolving EU policy context and legal framework creating momentum for the development of hydrogen activities in European ports areas

2021 (continued)

★ **(Recast) Directive on common rules for the internal markets in renewable and natural gases and hydrogen**, defining that 'low-carbon hydrogen' (blue hydrogen) must have a GHG emission reduction threshold of 70%; defining the rules that apply to in relation to unbundling of production and supply activities as well as access and storage of hydrogen.

State aid to promote the execution of important projects of common European interest, setting out the criteria following which the Commission will approve IPCEI with the State aid rules as of 2022 and stating green hydrogen projects are eligible for financial aid supports.

Global Gateway Initiative, stating that the EU will work with partner countries that have the potential to develop their renewable hydrogen production, and promote the creation of competitive markets to enable such hydrogen produced outside the EU to be traded internationally without export restrictions or price distortions.

2022

EU Taxonomy, setting a GHG emissions threshold for hydrogen production (3 tCO2e per tH2) for hydrogen production to be considered 'sustainable' (taxonomy-aligned) and stating that the production of machines that produce, store, transport, distribute and use hydrogen are automatically taxonomy-aligned.

Electrolyser Summit Joint Declaration, setting the objective to have in place by 2025 a combined annual electrolyzer manufacturing capacity in Europe of 17.5 GW (from 1.75 GW today), and to further increase that capacity by 2030 in line with projected demand for renewable and low-carbon hydrogen

REPowerEU, launching the Hydrogen Accelerator with a new target of 10 Mt of domestic renewable hydrogen production and 10 Mt of renewable hydrogen imports by 2030 (including 4 Mt in the form of ammonia); commitment to roll out an EU-wide scheme for (Carbon) Contracts for Difference and to mobilize EU funding (Horizon Europe, CEF, Cohesion Policy and RRF, InvestEU)[1].

The EU Strategy for Standardisation, identifying the need to address standardisation in the hydrogen value chain (i.e., hydrogen quality issues for injection into the pipeline network) as a priority.

EU Energy Platform, creating a voluntary coordination mechanism for the purchase of gas and hydrogen at EU level; commitment to setting up a dedicated work stream on joint renewable hydrogen purchasing under the EU Energy Platform.

EU External Energy Strategy, setting the objective to conclude hydrogen partnerships, notably in the EU's neighborhood and Africa, to facilitate the import of 10 Mt of hydrogen by 2030 and the development of local hydrogen markets; defining three major hydrogen import corridors: the North Sea region (Norway and UK), the Southern Mediterranean and Ukraine.

Global European Hydrogen Facility, aiming at setting up a common (EU-wide) approach to hydrogen diplomacy through the development of green hydrogen partnerships around the world.

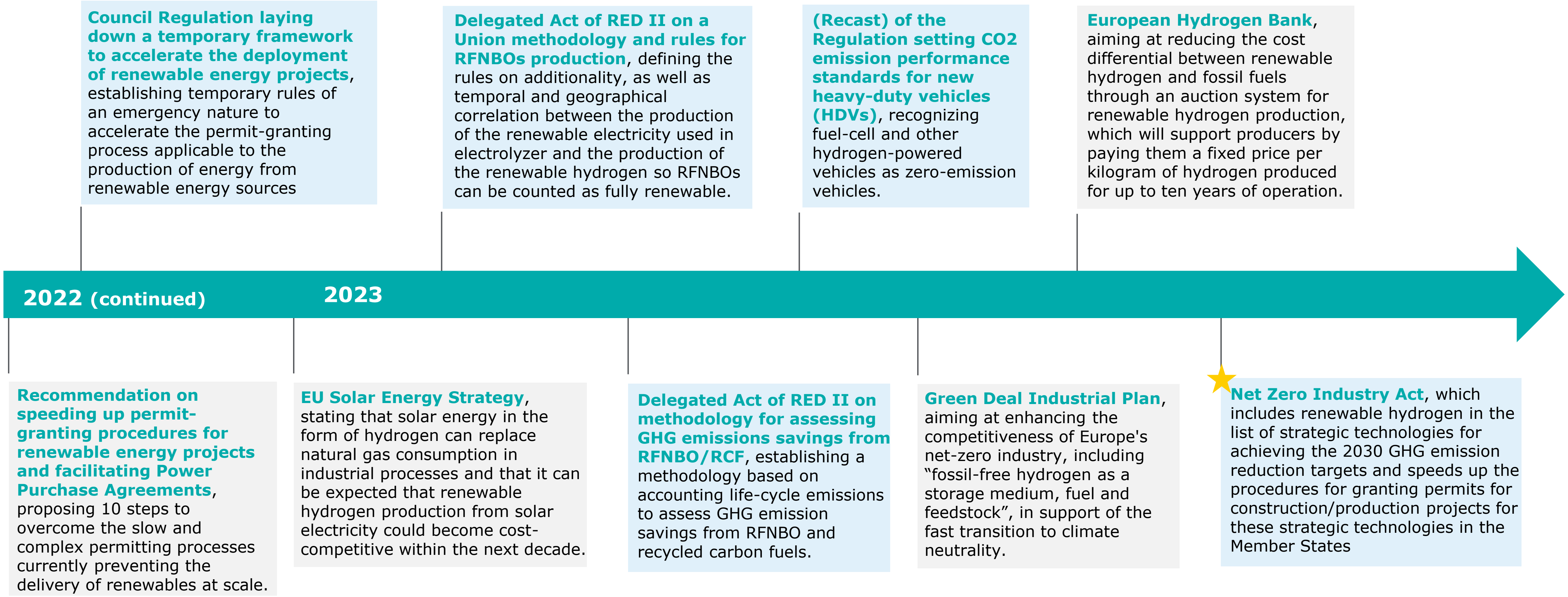
⬜ EU policy document and initiative

🟦 EU legislation

★ EU legislation still under debate (as of 07/2023)

<u>Notes</u>: (1) In the REPowerEU Communication, the Commission recognizes a role for nuclear-based hydrogen in substituting natural gas whereas overall, EU's focus is on renewable hydrogen, which, for now, it is the only type of hydrogen with dedicated end-use targets (in RED III).

A rapidly evolving EU policy context and legal framework creating momentum for the development of hydrogen activities in European ports areas



2022 (continued)

Recommendation on speeding up permit-granting procedures for renewable energy projects and facilitating Power Purchase Agreements, proposing 10 steps to overcome the slow and complex permitting processes currently preventing the delivery of renewables at scale.

Council Regulation laying down a temporary framework to accelerate the deployment of renewable energy projects, establishing temporary rules of an emergency nature to accelerate the permit-granting process applicable to the production of energy from renewable energy sources

EU Solar Energy Strategy, stating that solar energy in the form of hydrogen can replace natural gas consumption in industrial processes and that it can be expected that renewable hydrogen production from solar electricity could become cost-competitive within the next decade.

2023

Delegated Act of RED II on a Union methodology and rules for RFNBOs production, defining the rules on additionality, as well as temporal and geographical correlation between the production of the renewable electricity used in electrolyzer and the production of the renewable hydrogen so RFNBOs can be counted as fully renewable.

Delegated Act of RED II on methodology for assessing GHG emissions savings from RFNBO/RCF, establishing a methodology based on accounting life-cycle emissions to assess GHG emission savings from RFNBO and recycled carbon fuels.

(Recast) of the Regulation setting CO2 emission performance standards for new heavy-duty vehicles (HDVs), recognizing fuel-cell and other hydrogen-powered vehicles as zero-emission vehicles.

Green Deal Industrial Plan, aiming at enhancing the competitiveness of Europe's net-zero industry, including “fossil-free hydrogen as a storage medium, fuel and feedstock”, in support of the fast transition to climate neutrality.

European Hydrogen Bank, aiming at reducing the cost differential between renewable hydrogen and fossil fuels through an auction system for renewable hydrogen production, which will support producers by paying them a fixed price per kilogram of hydrogen produced for up to ten years of operation.

★ **Net Zero Industry Act**, which includes renewable hydrogen in the list of strategic technologies for achieving the 2030 GHG emission reduction targets and speeds up the procedures for granting permits for construction/production projects for these strategic technologies in the Member States

⬜ EU policy document and initiative

🟦 EU legislation

★ EU legislation still under debate (as of 07/2023)

The EU has put in place a wide range of funding mechanisms to support the large-scale deployment of green hydrogen along the EU value chain

Comprehensive list of **EU funding programs** and funds financed by the 2021-2027 long-term EU budget and NextGenerationEU[1;2]

EU funding instrument	Type of hydrogen project eligible for funding support
Connecting Europe Facility (CEF) - Energy	Cross-border hydrogen transmission & distribution projects; storage; electrolysers (>100MW).
Connecting Europe Facility (CEF) - Transport	Public hydrogen refueling stations on the TEN-T road, railway, sea and inland ports networks.
Cohesion Policy funds (ERDF, CF, REACT-EU)	*Eligibility of projects to the funding depends on the priorities defined in national and regional programs.*
Horizon Europe (Pillar II)	R&I projects trough the Clean Hydrogen Partnership (EUR 1bn), the European Partnership for Clean Aviation (EUR 735m) and the European Partnership for Clean Steel (among others).
Innovation Fund	Innovative technologies covered by Annex I to the EU ETS Directive, including electrolyser manufacturing and hydrogen end-use applications. The Commission will launch in autumn 2023 a first auction (i.e., competitive bid) for supporting the production of renewable hydrogen (budget of EUR 800 million). Winners of this auction will receive a fixed premium for each kg of renewable hydrogen produced over a period of 10 years.
Invest EU	Provides a budgetary guarantee to the European Investment Bank (EIB) and selected implementing partners with the aim to facilitate access to finance for riskier projects including green hydrogen production, on-site storage, transport refueling infrastructure and critical infrastructure supporting hydrogen deployment.
Just Transition Fund	*Eligibility of projects to the funding depends on the Just Transition Plans drafted by Member States.*
LIFE Program – Clean Energy Transition stream	Oriented to projects in early phase demonstration, in governance, and in catalyst projects for large-scale deployment solutions.
Modernisation Fund	Support hydrogen activities in lowest income EU countries, namely: the production and use of green hydrogen; hydrogen fueled trains, trucks and cars, high-efficiency hydrogen CHP.
The Recovery and Resilience Facility	*Eligibility of projects to the funding depends on the priorities defined in national Recovery and Resilience Plan.*
Important Projects of Common European Interest[3]	Large-scale electrolysers, infrastructure for the production, storage, and distribution of renewable and low-carbon hydrogen, fuel cells technologies, technologies for the integration of hydrogen into industrial and transport sectors.
European Hydrogen Bank	Guarantee the purchase of hydrogen and invest €3 billion to help build the future market for hydrogen.

Notes: (1) Hydrogen Public Funding Compass, 2022; (2) While the EU is deploying a wide range of support instruments to seize this industrial opportunity, **other countries are strengthening their manufacturing ambitions** in the hydrogen sector. For example, the **US Inflation Reduction Act** offers a streamlined incentive scheme for green hydrogen production, with a **tax credit of up to $3/kg**, forcing the EU to leverage regulatory stability and ecosystem value to overcome the risk of being outpaced by international competition in attracting investment; (3) IPCEI Hy2Tech and IPCEI Hy2Use.

EU Member States have accelerated their outreach actions and started securing some form of cooperation on hydrogen with non-EU partners

While the Commission intends to pursue a race to secure supply of green hydrogen **in a coordinated approach** through its newly created **Energy Platform**, only bilateral "hydrogen partnerships" agreements have been concluded so far*.

EU country	Partner country and date of announcement for state collaboration on hydrogen[1]	Total number of announced international collaborations
Germany	Japan (2019); Morocco (2020); Australia (2020 & 2021); Canada (2021 & 2022); Saudi Arabia (2021 & 2022); Chile (2021); Namibia (2021); Nigeria (2021); Ukraine (2022); India (2022); Angola (2022); Egypt (2022);	12
Netherlands	Namibia (2021); Chile (2021); South Africa (2021); Uruguay (2021); Oman (2021); Morocco (2021); Australia (2021); Canada (2022); United Arab Emirates (2022)	9
Belgium	Oman (2021); Namibia (2021); Chile (2021); Egypt (2022); Australia (2022)	5
France	India (2021); Canada (2021); Saudi Arabia (2022); United Arab Emirates (2022);	4
Italy	Saudi Arabia (2022), Algeria (2022)	2
Portugal	Morocco (2021)	*1*
Austria	United Arab Emirates (2022)	1
Greece	Saudi Arabia (2022)	1
EU	*Namibia (MoU on minerals and green hydrogen signed)[2]; Egypt and* Morocco *(Upcoming) as part of a wider Mediterranean Green Hydrogen Partnership[3]*	*3*

Note: *As of end of 2022, Table covers hydrogen trade related agreements and agreements that focus on technology co-operation, based on public announcements and is not exhaustive. Complementary to state collaborations, European private companies are also starting to develop cooperation programs on hydrogen production and export with non-European country (e.g., Port of Antwerp-Bruges with Port of Açu in Brazil). **Sources**: (1) Information compiled by GHERASIM, 2022 and IRENA, 2022, and completed by own research; (2) Hydrogen Europe, 2022; (3) EU external energy engagement in a changing world (JOIN(2022) 23 final).

European ports are natural gateways for hydrogen and hydrogen carriers flows to Europe's industries and transport networks

Driven by the unfolding of the REPowerEU plan, the accelerated emergence of a European green hydrogen and hydrogen carriers market will **result in fundamental economic and infrastructure developments** over the next decade and beyond, which will have a **significant impact on maritime and inland port areas.**

Although the expected transformations in ports as a result of the emergence of a European green hydrogen economy will be port-specific, **thorough understanding of the implications, requirements, and opportunities of the accelerated emergence of a green hydrogen market for port areas will enhance a successful transition, beneficial to all port-related stakeholders.**

Port areas as **direct users** of hydrogen and hydrogen carrier fuels

Like other commercial players, climate and energy policies will incentivize **key port stakeholders** (i.e., port authorities, terminal operators, etc.) to set decarbonization targets and **implement decarbonization solutions** for the **assets** and **operations under their purview**.

In particular, hydrogen/hydrogen carrier fuels **could play a role** in shifting away from the use of fossil fuels in the following activities:

- Maritime and inland **shipping**;
- **Onshore power supply** (cold ironing);
- **Cargo handling** and **terminal equipment**.
- **Industrial activities** located in port areas (e.g., refineries, ammonia plants, other chemicals, etc.)
- Refueling of **heavy-duty trucks** (for loading/unloading activities) in port areas

Port areas as a **provider of infrastructure** for hydrogen and hydrogen carriers

The unfolding of the green hydrogen economy will require the construction of **specific infrastructure** to **transmit**, **store**, **convert** and **supply end-users**, which is expected to have a fundamental impact on spatial planning and services within many European ports.

In particular, ports may offer a suitable location for the development of the following hydrogen and hydrogen carrier **infrastructure**:

- New sea or land-based **bunkering**;
- **Import** terminals;
- **Landing of offshore** produced **power**;
- Green hydrogen **production**;
- **Storage** in tanks;
- **Conversion** infrastructure;
- Multimodal hydrogen **refueling** stations.

Port areas as a **transit platform** for hydrogen and hydrogen carriers

European ports, and primarily those located along the **TEN-T** and/or **TEN-E core and comprehensive networks**, can be instrumental in the **transportation** and **supply** of hydrogen and hydrogen carriers.

In particular, since ports are often **connected** to nearby **industrial clusters**, **residential areas**, and **energy logistics nodes**, they could serve as a **natural transit hub** for the transport of hydrogen and hydrogen carriers to **multiple end-users** along the **coastal area** and into the **hinterland**. Ports can provide a suitable location for the **transportation** of hydrogen and hydrogen carriers by **pipeline**, **truck trailers**, **trains** and **inland ships** (barges).

The accelerated emergence of the European green hydrogen economy is expected to transform ports with regard to land use, the service needs of port customers, and the associated port facilities and energy infrastructure

While the expected transformations in ports as a result of the emergence of a European green hydrogen economy will be port-specific, with different implications expected for sea and inland ports, the growing demand and supply of hydrogen and hydrogen carriers will likely have far-reaching implications for **land use**, port **services** and **facilities**, **energy infrastructure**, **energy flows**, **industrial activities**, and **transportation services** in ports.

Space

Land-use trade-off

- Land availability in the port area
- Spatial development & planning
- Transition from the current setup
- Safety zone requirements
- Modal shift in transport

Facilities

Service new energy

- Land-base cargo handling and terminal equipment
- Port vessels
- New maritime fuel bunker facilities
- Multimodal hydrogen refueling stations
- Onshore power supply (cold ironing)

Infrastructure

Enable new energy

- Dedicated terminals and quays
- New on-/off loading facilities
- Landing of offshore produced power
- Green hydrogen production
- Storage in tanks
- Conversion infrastructure

Energy flows

New energy flows & processes

- Deep sea transport of hydrogen and hydrogen carriers via tankers
- Hydrogen storage in offshore underground geological formations
- Energy integration via power cables and pipeline infrastructure

Industry

New technology & clusters

- Industrial processes with hydrogen (carriers) demand (e.g., refined oil, biofuels, synfuels, chemicals, etc.)
- Industrial relocation in the vicinity of ports
- New industry and local production (e.g., offshore wind, electrolyzer)

Hubs

Connectivity and alliances

- Connection to nearby industrial clusters
- Connection to nearby residential areas
- Multimodal transportation to the hinterland via pipeline, truck trailers, trains and inland ships

Areas of change for ports due to integration of hydrogen and hydrogen carriers flows, adapted from Royal HaskoningDHV, 2022.

Framework of the study

This study aims to inform relevant port-related stakeholders and policy makers on the areas of priority for R&I projects, safety regulations, codes and standards and non-technical enablers for the timely development of hydrogen-related activities and infrastructure in EU port areas

Three layers of analysis for each of the steps of the hydrogen value chain that can have a significant impact on activities and infrastructure in EU port areas

Description of the activity, context and background

R&I challenges and associated recommendations

Assessment of current **technological challenges,** identification of **areas of priority for R&I** projects and **recommendations on R&I objectives** and millstones (e.g., cost target, research timeline)

Safety challenges and associated recommendations

Identification of **gaps** in **safety regulations, codes** and **standards** and **recommendations** on safety regulations, codes and standards to update or develop.

Non-technical (policy, regulatory, strategic, etc.) challenges and associated recommendations

Identification of **non-technical (policy, regulatory, strategic, etc.) challenges** that are hampering the scale-up of hydrogen-related activities in port and maritime areas and **recommendations** on these non-technical(policy, regulatory, strategic, etc.) challenges.

Although the transformations, opportunities and challenges expected in ports as a result of the emergence of a European green hydrogen economy will be very much port-specific, **the recommendations on strategic actions for port authorities and other port-related stakeholders outlined in this report are intended to encompass the entire European port ecosystem**, and are therefore not tailored to any particular port archetype (e.g., seaport or inland port, logistics and transport, urban, industrial, or fueling). **The report is designed in such a way as to allow port authorities (of all port archetypes) and other port-related stakeholders to navigate easily through the relevant considerations for hydrogen or hydrogen carriers-related activities of interest to them** (depending on the port's specific commercial strategy).

Defining the scope of this study in a context of a changing EU policy and regulatory framework

The **primary objective of this study** will be to **inform EU** and **Member States policymakers**, but also **port authorities** and **other port stakeholders** on 1) **areas of priority for R&I projects**, 2) **safety-related regulations, codes and standards** and 3) **non-technical (policy, regulatory, strategic, governance, investments, etc.) provisions** that are recommended **for the timely development of hydrogen and hydrogen carrier-related activities and infrastructure in port areas**.

⚠ As the legislative framework establishing the EU policy and regulatory landscape for the hydrogen sector is in process at the time of this study (debate and negotiation is ongoing at EU level), **this document will not formulate policy recommendations on specific provisions in scope of these ongoing legislative dossiers** (e.g., ETD, Hydrogen and Decarbonised Gas Market Package, TEN-T Regulation etc.).

In the scope of this study

- Institutional and organisational **governance** of hydrogen and hydrogen carriers-related activities and infrastructure in port areas.
- **Strategic considerations for port authorities and port-related stakeholders** that can influence the development of hydrogen and hydrogen carriers-related activities and infrastructure in their port areas
- **EU and national** (at the Member States level) **policy initiatives** (including **public funding**) that can have an impact on the efficient, rapid and large-scale development of hydrogen and hydrogen carriers-related activities and infrastructure in port areas.
- **EU and international** (e.g., at the level of the IMO) **regulatory framework** that can have an impact on the development the efficient, rapid and large-scale development of hydrogen and hydrogen carriers-related activities and infrastructure in port areas.
- **Areas of priority for R&I in technologies and infrastructure** that are required or have the potential to foster the scale-up of hydrogen and hydrogen carriers flows in port areas.
- **Safety regulations, code and standards** pertaining to hydrogen and hydrogen carrier-related activities in port areas.

Outside the scope of this study

- EU regulatory and policy **framework** for the development of **renewable power** (e.g., wind offshore, wind onshore, solar PV) **capacity**.
- Regulatory provisions defining **rules for hydrogen to account towards** EU energy and climate **targets** and rules for **assessing GHG emissions savings**.
- Regulatory provisions defining **rules for the development and interoperability of trans-European GH2 transport networks** as well as associated infrastructure (i.e., pipelines).
- Regulatory **provisions setting demand/supply targets for specific sectors** (industries, transport) **and/or sub-sectors**.
- Regulatory **provisions** rules and conditions for the **deployment of hydrogen** charging infrastructure and **refueling stations along the Ten-T core and comprehensive networks**.
- EU regulatory and policy **framework for carbon taxation** (i.e., EU-ETS and CBAM), and **energy taxation** (ETD).
- EU and national **strategies** for the **development of partnerships with non-European countries for import of hydrogen** (i.e., origin of imports).
- Choices on **which EU funding to mobilize** for hydrogen activities.

Note: (1) Given the ongoing legislative work to revise the EU *Regulation on the internal market for renewable and natural gases and hydrogen* (COM/2021/803 final) and the EU *Directive on common rules for the internal markets in renewable and natural gases and hydrogen* (COM/2021/803 final) (so called 'gas package') aiming at defining the rules for the development and interoperability of trans-European GH2 transport networks systems, and since decisions related to the construction of dedicated hydrogen pipelines or to the retrofitting of existing fossil gas pipelines are taken by Member States governments (through their respective Transmission and Distribution System Operators), and not by port authorities and related stakeholders, the activity consisting of transporting hydrogen through pipelines from the place of production to the place of consumption is **out of the scope of this study**.

Considerations regarding the development of blue hydrogen activities and associated value chain in port areas are beyond the scope of this study

Blue hydrogen-related activities in port areas …

Large-scale European blue hydrogen production has the theoretical potential to decarbonize current hydrogen uses as well as new industrial and non-industrial hydrogen applications, while paving the way for a European green hydrogen economy.

- Producing very large quantities of green hydrogen within the EU is subject to public acceptance of an accelerated expansion of renewable installed capacity which goes much beyond planned expansions formulated in the current National Energy and Climate Plans (NECPs).
- **Assuming natural gas is available in sufficient quantities**, the technical potential for blue hydrogen production is theoretically limited only by CO_2 storage, the potential of which far exceeds the total projected hydrogen demand, even if it were fully met by blue hydrogen[1].
- Assuming natural gas supply in Europe is **available at a relatively low-cost** (compared to alternative low-carbon energy options), and that **technically efficient carbon capture and storage systems are cost-competitive**, blue hydrogen could support emissions reductions and accelerate the pace of the transition to low carbon/renewable hydrogen, particularly in the market ramp-up phase (2020s and 2030s), when the potential for green hydrogen supply from dedicated renewables alone may be insufficient to meet local and regional demand.
- Beyond 2035, the deployment of new blue hydrogen projects is likely to face **increasing competition from green hydrogen** (domestic and imported) as the latter becomes more widely available at lower cost. However, existing (by then) blue hydrogen projects, which have a 25-year lifespan, could still have a role to play as a marginal supply option and could contribute to system integration and balancing of variable green hydrogen through steady baseload hydrogen production.

… are beyond the scope of this study

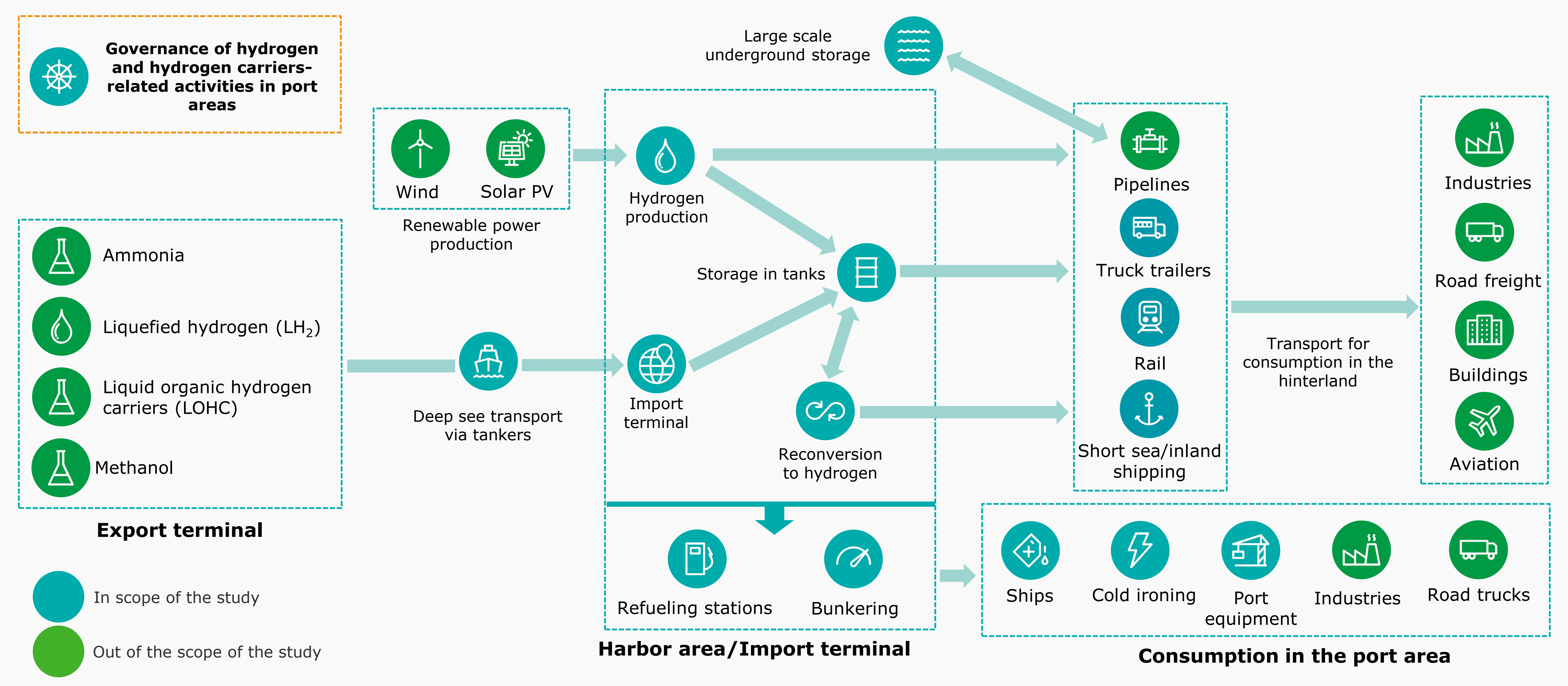
Due to significant political, regulatory, economic and technological barriers, this study assumes that the large-scale potential of European blue hydrogen production will not be harnessed.

- Starting with the EU Hydrogen Strategy (2020), emphasized in the "Fit for 55" policy proposal package (2021) and endorsed in the REPowerEU Communication (2022), **the EU has consistently outlined that institutional efforts** for the development of a hydrogen economy by 2030 and beyond **will be geared towards green hydrogen**[1].
- Therefore, given such **strong political impetus** for green hydrogen development at the EU level, which has been explicitly followed by most Member States, along with the fact that CCS technologies today faces strong **regulatory and political acceptance constraints** in most of the EU Member States (limiting the rollout of public subsidies schemes in support of blue hydrogen production)[3], as well as technological uncertainties[4], **considerations regarding the development of blue hydrogen activities and associated value chain in port areas are beyond the scope of this study**.

⚠ Even though blue hydrogen is out of scope, most of the recommendations formulated in this report could also be valid for the development of blue hydrogen-related activities in port areas.

Notes: (1) Guidehouse, 2021; (2) In the proposal for a recast RED, blue hydrogen is not recognized as contributing to the goal of 50% low carbon/renewable hydrogen in total hydrogen used for energy and non-energy end uses in industry by 2030. The **REPowerEU communication** sets ambitious roadmaps for reducing natural gas consumption in the EU. This major policy shift leads to disregarding the rollout of blue hydrogen production in Europe and upholds a bold political will to focus exclusively on the scale-up of green hydrogen production and imports; (3) In an economic environment characterized by **high natural gas** and **carbon prices** on European market, and with **little or no public subsidies** for the development of blue hydrogen production projects in most European countries, it can be expected that blue hydrogen will encounter stiff competition from alternative decarbonization solutions (i.e., electrification, biomethane), from large-scale European green hydrogen projects and from hydrogen imports, therefore limiting large-scale deployment perspectives; (4) Due to high **uncertainties in the capture rate of CCS** technologies for hydrogen production and the risks of **methane leakage** from natural gas during exploration and transportation, blue hydrogen can only play a transitional role in contributing to the EU's 2050 net-zero goal, **challenging the long-term** (up to 25 years) **economic viability** of blue hydrogen projects.

An approach aiming at covering all steps of the hydrogen value chain that can have a significant impact on activities and infrastructure in EU port areas



Activities and infrastructure related to hydrogen and hydrogen carriers in port areas can be articulated around three main areas of influence, all under the umbrella of an institutional and organizational ecosystem governance

Governance of hydrogen and hydrogen carrier-related activities and infrastructure in port areas

Three main areas of influence of hydrogen and hydrogen carriers-related activities and infrastructure in port areas

In the port

- Import terminals of hydrogen and hydrogen carriers in EU ports
- Bunkering of hydrogen and hydrogen derivatives
- Use of hydrogen and hydrogen-based fuels in the maritime sector
- Use of hydrogen and hydrogen carriers in cold ironing
- Use of hydrogen and hydrogen carriers in port equipment

In the vicinity of the port[1]

- Renewable hydrogen production in ports areas
- Surface hydrogen and derivatives storage solutions
- Conversion of imported hydrogen carriers into hydrogen
- Multimodal land-based hydrogen refueling stations
- Transport of hydrogen and derivatives from ports to users

In the wider setting of the port area

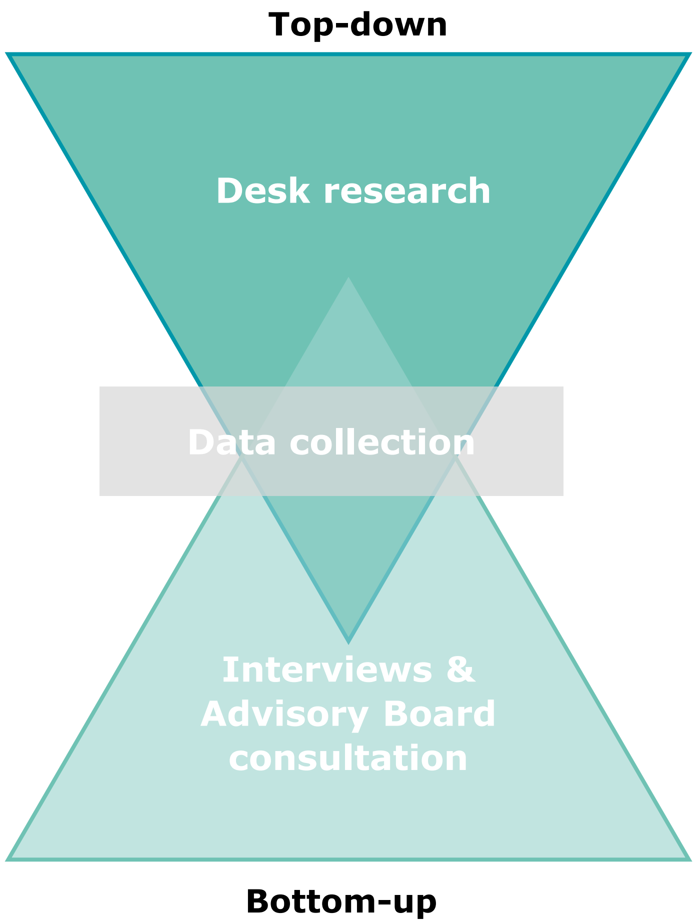
- Deep sea transport of hydrogen and hydrogen carriers via tankers
- Hydrogen storage in underground geological formations

⚠ Throughout this report, the reader is advised to bear in mind that **the European market for green hydrogen** and hydrogen derivatives as an energy carrier **is still in its early stages**. To achieve the 2030 ambitions outlined in the REPowerEU plan, **pilot projects** in all types of hydrogen activities and infrastructure in port areas **will need to be rapidly deployed**, **from which lessons will be learned** to enable subsequent rapid roll-out. During these developments, **coalitions between port authorities and other key port-related stakeholders across Europe will be critical to success**.

Note: (1) Although industrial activities (e.g., refined oil, biofuels, synfuels, ammonia, circular chemical processes, primary steel, methanol etc.) located in in the wider port area are expected to be among the first end-users of green hydrogen, associated industrial infrastructure are out of the scope of this study.

A methodology combining top-down and bottom-up approaches

This study is based on a **mixed qualitative approach** involving a non-systematic analytical **desk research**, **interviews with key stakeholders and experts**, and a **consultation conducted with the members of the Advisory Board** of this study. The use of a mixed qualitative approach allows this study to gather relevant data from the existing literature to draw out initial high-level analyses, and then to unlock knowledge collectively shared by the relevant stakeholders.



Desk research

In order to prepare for the interviews, desk research has been performed as a first step. The desk research focused on available literature and serve the purpose of identifying relevant legislation, contextual elements, issues, as well as existing studies and reports. Based on consolidated findings from the desk research, some key insights have been drawn and enabled the fine-tuning of the interview guide.

Stakeholder and expert interviews

The primary purpose of conducting targeted interviews with key stakeholders in the European port ecosystem is to support, supplement, or reject the preliminary findings from the initial desk research with a richer set of qualitative data, therefore enhancing the quality and validity of the research findings, as well as better reflect multiple perspectives.

Semi-structured 1-hour interviews were conducted with the following type of stakeholders:

- Port authorities
- Terminal operators
- Shipbuilding companies and ship operators
- Energy infrastructure providers
- International organisations
- Interest groups & Associations

Advisory Board consultation

The preliminary policy and practical recommendations drafted on the basis of the results of the analyses of technical, technological and safety-related barriers and gaps hindering the development of hydrogen-related activities and infrastructure in port areas were presented to the Advisory Board of this study, allowing the recommendations to be sharpened in line with key stakeholders' concerns.

Illustrative example of the structure of the analysis for one step of the hydrogen value chain in EU port areas

Bunkering of hydrogen and hydrogen derivatives

Photo: Shell

Bunkering of hydrogen and hydrogen derivatives

Introduction: Ports will need to timely develop hydrogen and/or hydrogen carrier bunkering infrastructures for maritime and inland shipping

Description of the activity: Bunkering of hydrogen/hydrogen carriers (i.e., ammonia, methanol) for use as fuel by ships, including *shore-to-ship* (fuel bunkered directly from a storage tank or pipelines), *ship-to-ship* (fuel bunkered from cargo tanks of a refueling vessel)[1] and *truck-to-ship* (fuel bunkered from a truck connected to the ship on the quayside)[2], but also floating ammonia bunkering systems and swappable compressed hydrogen (GH2) containers.

Context and background:

- With the upcoming adoption of the FuelEU Maritime Regulation[4] and already adopted IMO targets[5] and Act of Mannheim[6] (inland EU shipping), the maritime sector is under increasing pressure to accelerate emissions reductions, notably through the **gradual replacement of fossil-fuel powered vessels with low-carbon alternative fuels**. In this context, while the uptake of specific low-carbon alternative maritime fuels is largely driven by shipping companies, **sea and inland ports can play a catalytic role in offering, promoting and using alternative maritime fuels**. Indeed:
    1. Firstly, while numerous alternative maritime fuels are being touted as the future of ships (i.e., compressed or liquid hydrogen, methanol, ammonia, synthetic fuels) and there is no clear answer as to which fuel or combination of fuels will be most prevalent, **ports have no choice but to already plan now in order to be in the position to provide the right fuels in sufficient quantities and in a timely manner**, while meeting the diverse and complex safety and handling requirements associated with these fuels.
    2. Secondly, **ports can also play a user role by using these alternative fuels to decarbonize their own port vessel fleet**.
    3. Thirdly, **ports can act as a promoter of alternative maritime fuels, notably by raising awareness within the port community and wider public** in order to push progress and direction of alternative fuel use and adoption in cooperation with relevant stakeholder.
- In this context, **ports will eventually need storage facilities from which bunkering infrastructures** (i.e., vessels) **will be able to source alternative fuels and supply them to ships** that need them. In the case of small vessels based in ports, bunkering from a fixed barge may be another option[7].

Ammonia bunkering infrastructure protype by AZANE Fuel Solutions (Source: link)

Notes: (1) Ship-to-ship bunkering is most commonly used for seagoing vessels, as the supply vessel can be moored alongside the ship while it undergoes simultaneous cargo handling; (2) Truck-to-ship bunkering is most appropriate for smaller vessels, as volumes are small, and throughput is low; (3) Bunkering of GH2 in swappable containers integrates well with the existing logistics operations of inland navigation companies that handle containers. However, site safety requirements are required, and permits are needed. (4) The FuelEU Maritime proposal (COM/2021/562 final) requires that the yearly average greenhouse gas intensity of the energy used on-board by a ship during a reporting period shall be reduced by -2% from 2025, -6% from 2030, -13% from 2035, -26% from 2040, 59% from 2045 and -75% from 2050, compared to the fleet average greenhouse gas intensity of the energy used on-board by ships in 2020; (5) The initial targets by the IMO are set to reduce carbon intensity of international shipping by 40% by 2030, and 70% by 2050 (compared to 2008). Moreover, the total annual GHG emissions need to be reduced by 50% compared to 2008 across international shipping; (6) To further improve the ecological sustainability of inland navigation, the Act of Mannheim (2018) tasked the Central Commission for the Navigation of the Rhine (CCNR) to develop a roadmap in order to reduce GHG emissions by 35% compared with 2015 by 2035, reduce pollutant emissions by at least 35% compared with 2015 by 2035 and largely eliminate GHG and other pollutants by 2050; (7) For smaller vessels, a distinct bunkering infrastructure may be required, given that they exhibit different physical compatibility and throughput rates than larger vessels (e.g., such as container ships).

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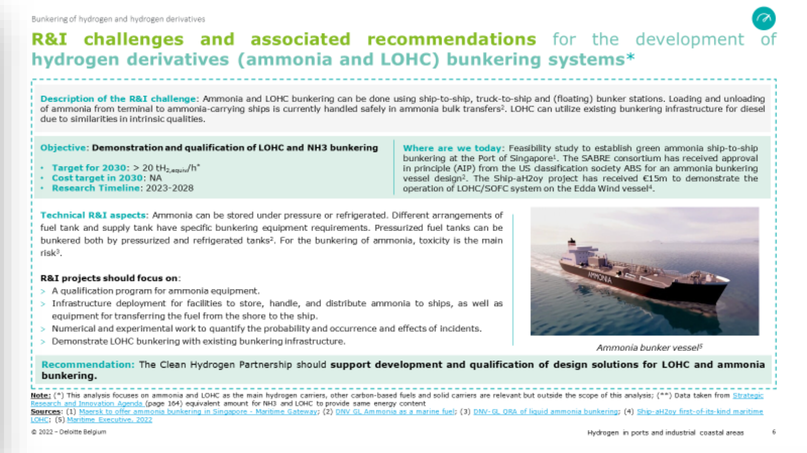
Hydrogen in ports and industrial coastal areas 3



Bunkering of hydrogen and hydrogen derivatives

R&I challenges and associated recommendations for the development of hydrogen derivatives (ammonia and LOHC) bunkering systems*

Description of the R&I challenge: Ammonia and LOHC bunkering can be done using ship-to-ship, truck-to-ship and (floating) bunker stations. Loading and unloading of ammonia from terminal to ammonia-carrying ships is currently handled safely in ammonia bulk transfers[2]. LOHC can utilize existing bunkering infrastructure for diesel due to similarities in intrinsic qualities.

Objective: **Demonstration and qualification of LOHC and NH3 bunkering**

- **Target for 2030**: > 20 $tH_{2,equiv}/h^{*}$
- **Cost target in 2030**: NA
- **Research Timeline**: 2023-2028

Where are we today: Feasibility study to establish green ammonia ship-to-ship bunkering at the Port of Singapore[1]. The SABRE consortium has received approval in principle (AIP) from the US classification society ABS for an ammonia bunkering vessel design[2]. The Ship-aH2oy project has received €15m to demonstrate the operation of LOHC/SOFC system on the Edda Wind vessel[4].

Technical R&I aspects: Ammonia can be stored under pressure or refrigerated. Different arrangements of fuel tank and supply tank have specific bunkering equipment requirements. Pressurized fuel tanks can be bunkered both by pressurized and refrigerated tanks[2]. For the bunkering of ammonia, toxicity is the main risk[3].

R&I projects should focus on:

- A qualification program for ammonia equipment.
- Infrastructure deployment for facilities to store, handle, and distribute ammonia to ships, as well as equipment for transferring the fuel from the shore to the ship.
- Numerical and experimental work to quantify the probability and occurrence and effects of incidents.
- Demonstrate LOHC bunkering with existing bunkering infrastructure.

Ammonia bunker vessel[5]

Recommendation: The Clean Hydrogen Partnership should **support development and qualification of design solutions for LOHC and ammonia bunkering.**

Note: (*) This analysis focuses on ammonia and LOHC as the main hydrogen carriers, other carbon-based fuels and solid carriers are relevant but outside the scope of this analysis; (**) Data taken from Strategic Research and Innovation Agenda (page 164) equivalent amount for NH3 and LOHC to provide same energy content

Sources: (1) Maersk to offer ammonia bunkering in Singapore - Maritime Gateway; (2) DNV GL Ammonia as a marine fuel; (3) DNV- GL QRA of liquid ammonia bunkering; (4) Ship-aH2oy first-of-its-kind maritime LOHC; (5) Maritime Executive, 2022

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Bunkering of hydrogen and hydrogen derivatives

Safety challenges and associated recommendations for the development of alternative fuels bunkering infrastructures for maritime and inland shipping

Description of the safety challenge: The handling and bunkering of all hydrogen-based maritime fuels (like gaseous hydrogen, (cryo)compressed hydrogen, liquid hydrogen, ammonia, methanol, liquid organic hydrogen carriers, metal hydrides) in a port environment are associated with potential safety hazards (explosion, fire, toxicity) that can have an immediate impact on the physical safety of people, building structures and equipment in the direct proximity.

Objective: **Development of a set of safety regulations, codes and standards for enabling safe hydrogen-based fuel bunkering activities in a port environment.**

Where are we today: Bunkering guidelines, procedures, standards and checklists for bunkering of hydrogen-based fuels do not exist[1]. CEN/CENELEC are in the early stages for developing standards for bunkering hydrogen[2]; some generic inputs can be retrieved from Norwegian standard FOR-2009-06-602 (does not cover hydrogen)[3]. Experience with the loading and unloading of sea going vessels carrying methanol and ammonia is available. Although different from bunkering, overlap in lessons learned are to be considered[4].

Safety projects should focus on:

- Assessment of the cyclic thermal effects on durability and integrity of storage tanks and hoses during direct gaseous hydrogen fueling; design considerations and integrity of hoisted (swappable) fuel containers to survive unintentional drops from the swapping cranes.
- Ventilation considerations in terms of position of vent pipes relative to living quarters and height above deck; installation of gas detectors in fresh air ventilation to accommodation and working spaces.
- Firefighting systems appropriate for hydrogen carrier used and fire loads anticipated; fire integrity of the fuel tank; fire detection systems and their measurement locations.
- The location of the bunkering infrastructure in relation to the safety distance required; distances differ per phenomenon - toxicity (ammonia), overpressure (explosion) and heat radiation (explosion/fire); Determination of scale of the operations in light of the more stringent guidelines of SEVESO III (5 tonnes limit).

Recommendations:

- The EU should encourage the ISO and CEN/CENELEC to develop bunkering guidelines/standards; make use of existing and corresponding documents for the bunkering of LNG. Basic principles will be similar, and the operational and safety requirements will be different.
- The EU should encourage the International Association of Classification Societies (IACS) and Society for Gas as a Marine Fuel (SGMF) to provide a more specific and practical bunkering guidelines for the implementation of the international guidelines.
- The EU should encourage bunker operators to develop bunker procedures with support from the classification societies.
- The EU should encourage the International Association of Ports and Harbors (IAPH) to develop harmonized bunker checklists.
- The EU should develop a roadmap to harmonize maritime regulations with EU onshore regulations, national regulations and Port Authorities prescriptions to support the definition of practical solutions.

Sources: (1) WPSP, 2023; (2) European Clean Hydrogen Alliance, 2023; (3) RH2INE Kickstart Study, 2022; (4) Van Hoecke et al., 2021

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Bunkering of hydrogen and hydrogen derivatives

Non-technical challenges associated with the development of **alternative fuels bunkering infrastructures for maritime and inland shipping**

Non-technical barriers hindering the efficient, rapid and large-scale **development of alternative fuels bunkering infrastructures for maritime and inland shipping:**

1. Lack of **port-specific roadmaps/planning** developed by port authorities in collaboration with future hydrogen (derivatives) bunkering fuel companies, alternative fuel storage owners, terminal operators and shipping companies **to precisely define governance, as well as key milestones and conditions for the development of alternative fuel bunkering activities in ports** (i.e., timing, quantities, end-users, required infrastructures, investment needs, etc.).
2. Lack of **consensus on what will be the future fuels mix of choice in the maritime sector** (e.g., ammonia, methanol, e-fuels, LH_2, GH2), preventing hydrogen and hydrogen carrier bunkering infrastructures from moving from the R&D phase to wider adoption.
3. With the likely expansion of several alternative marine fuels in the coming years, various bunkering options with different technological requirements will be needed[1]. This situation may lead to **increased pressure in ports that are already facing land scarcity**, **as separate bunkering installations require more and different berthing points**, and **large safety zone requirements may be needed** for at least some of these alternative fuels (e.g., ammonia)[2;3].
4. Lack of sufficient **demand and supply** (availability of alternative maritime fuels in ports in sufficient quantities) **certainties for hydrogen/hydrogen carriers-based bunkering fuels** to incentivize seaports (i.e., terminals, bunker operators and/or other third parties to invest in dedicated bunkering infrastructures (e.g., filling points and bunker barges).
5. Lack of **EU-wide harmonized technical and safety protocols,** as well as **regulatory framework** (including clear guidelines to Member States on administrative practices and permitting procedures) for the construction and safe operation of hydrogen and hydrogen carriers bunkering infrastructures in the shipping sector.
6. Lack of **harmonized operational practices between Member States for ship bunkering**, resulting in the need to design and build several types of bunkering infrastructure for each (alternative) maritime fuel, adapted to the bunkering specificities of the Member States.
7. Lack of **innovation breakthroughs** to further improve the efficiency and safety in handling and bunkering alternative fuels.

Note: (1) For instance, while LH2 requires highly insulated containers with cryogenic hoses for bunkering, ammonia is corrosive and toxic and need specialized equipment to eliminate any potential for leakage. Even though battery-electric propulsion seems to display great viability for inland vessels or port support vessels, innovative bunkering solutions such as containerized fuel tanks for GH2 enables simplified bunkering and can initiate the use of hydrogen in inland shipping; (2) While an adequate dedicated area for fuel handling and bunkering would be required for all alternative maritime fuels, the bunkering of ammonia is expected to need substantially larger safety distances around locations where ship-to-ship bunkering takes place than GH2, LH2 or methanol; (3) Additionally, given that energy density of alternative maritime fuels are substantially less per volume than traditional fossil fuels, more space is required on top of the additional space needed to adhere to safety distances.

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Bunkering of hydrogen and hydrogen derivatives

Recommendations for addressing non-technical challenges related to the development of **alternative fuels bunkering infrastructures** for shipping (1/2)

Responsible authority(ies): **Port authorities and other port stakeholders**

① As the adoption of alternative marine fuels becomes more widespread, **all port authorities with bunkering operations in their ports need to consider how best to develop bunkering infrastructure for alternative fuels**, either by taking on this responsibility themselves or by using third-party bunkering services in their port. To do so, under the leadership of port authorities, **port areas** (terminal operators, alternative fuel storage owners, fuel/bunker production company and shipping companies) **should define a framework** (e.g., governance, timing, quantities, end-users, required infrastructures, investment needs, space availability etc.) **for the development of alternative maritime fuels bunkering infrastructures** that promotes and drive supply and demand dynamics of these fuels.

② Should port authorities not directly responsible for the development and operation of alternative fuel bunkering infrastructures, they should **actively contribute to encouraging**, **stimulating**, or **compelling** (depending on port governance and regulatory powers) **private fuel bunkering operators** to timely develop and operate alternative fuel bunkering infrastructures. For instance, This incentivization can be done by:

- **Altering regulatory frameworks**, **providing guidance** (i.e., in coordination with relevant societies and associations), or **including specific provisions** in tender specifications or terminal concession contracts.
- **Investing in specific flagship demonstration projects** to prove the technical and economic feasibility of safely handling and bunkering alternative fuels.
- **Providing support to identify and secure access to** European and/or national **public funding** programmes.
- **Providing training support** for personnel of bunkering operators on the safely operation and maintenance of alternative fuel bunkering infrastructures.

③ Pending the development of IMO and ISO technical regulatory standards, **relevant stakeholders** (e.g., classification societies), **could align** themselves to **establish harmonized technical and safety standards** for bunkering of alternative maritime fuels as well as **technological standards for building alternative maritime fuel bunkering infrastructures and equipment** used in Member States.

④ Due to the spatial requirements of building and operating the various bunkering infrastructures associated with the likely expansion of several alternative maritime fuels, sea and inland ports **with space limitations** may be able to bypass their own alternative bunkering requirements by **contracting with larger ports or nearby alternative fuel providers for bunkering of specific fuels**. In turns, **ports could also consider to specialize in specific alternative maritime fuels** that will also supply other ports in the same coastal area.

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The long-term scaling up of hydrogen-related infrastructure in port areas is inextricably tied to overarching cross-topical policy considerations (1/2)

Providing EU and national support to first movers through enhanced and easily accessible public/private R&I programmes[1]

- **Geographical prioritization of public funding allocation**. The EU could prioritize its funding for the development of hydrogen and hydrogen carrier-related demonstration projects and infrastructure in ports areas in Member States where public (national) and/or private funding for these projects are insufficient despite clearly favorable socio-economic, technical and climatic conditions.
- **Prioritization of a value chain integrated approach for public R&I subsidy calls**. The EU and Member States could prioritize the adoption of an integrated approach (i.e., encompassing multiple complementary projects along the hydrogen value chain in ports in the same subsidy call) when allocating public funding to the development of hydrogen-related demonstration projects in port areas.
- **Allowing targeted exemptions for facilitating R&I projects in port areas**. As proposed by the European Commission in May 2022[2], Member States could put in place regulatory sandboxes to grant targeted exemptions from the national, regional or local regulatory framework on the applicable rules to launch the development of pilot demonstration projects in port areas. In particular, instead of being required to go through long and complex bidding process, publicly-owned port authorities could be given greater autonomy to determine the terms and conditions for awarding permits and land to hydrogen-related pilot project developers.

Developing and enforcing the appropriate policy framework for enabling large-scale import of green hydrogen and hydrogen carriers in the EU

- **Elaboration of a green hydrogen certificates mechanism** (**also known as "guarantees of origin”**). Once the applicable rules defining under which conditions can green hydrogen be counted as fully renewable under EU targets, the EU could develop a robust certification scheme relying on so called “voluntary schemes” that would allow imported hydrogen/hydrogen carriers (e.g., ammonia, methanol) to be counted towards EU renewable energy and climate targets and transported across borders within the EU.
- **Definition of international quality standards**. In close collaboration with relevant international (non-EU) stakeholders, the EU could contribute to the development of international standards, with clear technical and safety specifications, for the quality of hydrogen to be produced, transported (pipelines or LH_2/hydrogen carrier tankers) and used.
- **Establishment of a support scheme for international hydrogen import projects.** Considering that a temporary effort to close the funding gap for selected hydrogen import cases should contribute to provide the impetus to develop the import pathway, the EU could support the development of a coordinated EU-wide support scheme (such as, for instance, contracts for difference or carbon contracts for difference) that would allow early off takers to consume the first necessary imported renewable volumes while, in turn, allowing non-EU hydrogen or hydrogen carrier suppliers to secure long-term hydrogen purchase agreements[3].

Notes: (1) In a context of increasing hydrogen ambitions in other countries (e.g., the U.S. Inflation Reduction Act, which offers a streamlined incentive system for green hydrogen production, with a tax credit of up to $3 per kilogram), the EU will not only benefit from greater regulatory stability, but also from more streamlined and easily accessible public R&I programs, so as not to be outpaced by international competition to attract R&I investments; (2) Article 32 of the Commission Recommendation on speeding up permit-granting procedures for renewable energy projects (C(2022) 3219 final); (3) For instance, best practices can be drawn for the H2Global (Germany) scheme, designed specifically for imports and which could serve as a blueprint for incentivizing imports to Europe (see H2Global, 2022).

The long-term scaling up of hydrogen-related infrastructure in port areas is inextricably tied to overarching cross-topical policy considerations (2/2)

Speeding-up and simplifying permit-granting procedures for all hydrogen-related projects in port areas

For all relevant activities and infrastructure at all steps of the hydrogen value chain in port areas, **Member States should, as soon as possible, adopt the measures proposed by the European Commission on speeding up permit-granting procedures for renewable energy projects**[1]. In particular, the following actions should be carried out by competent authorities in Member States:

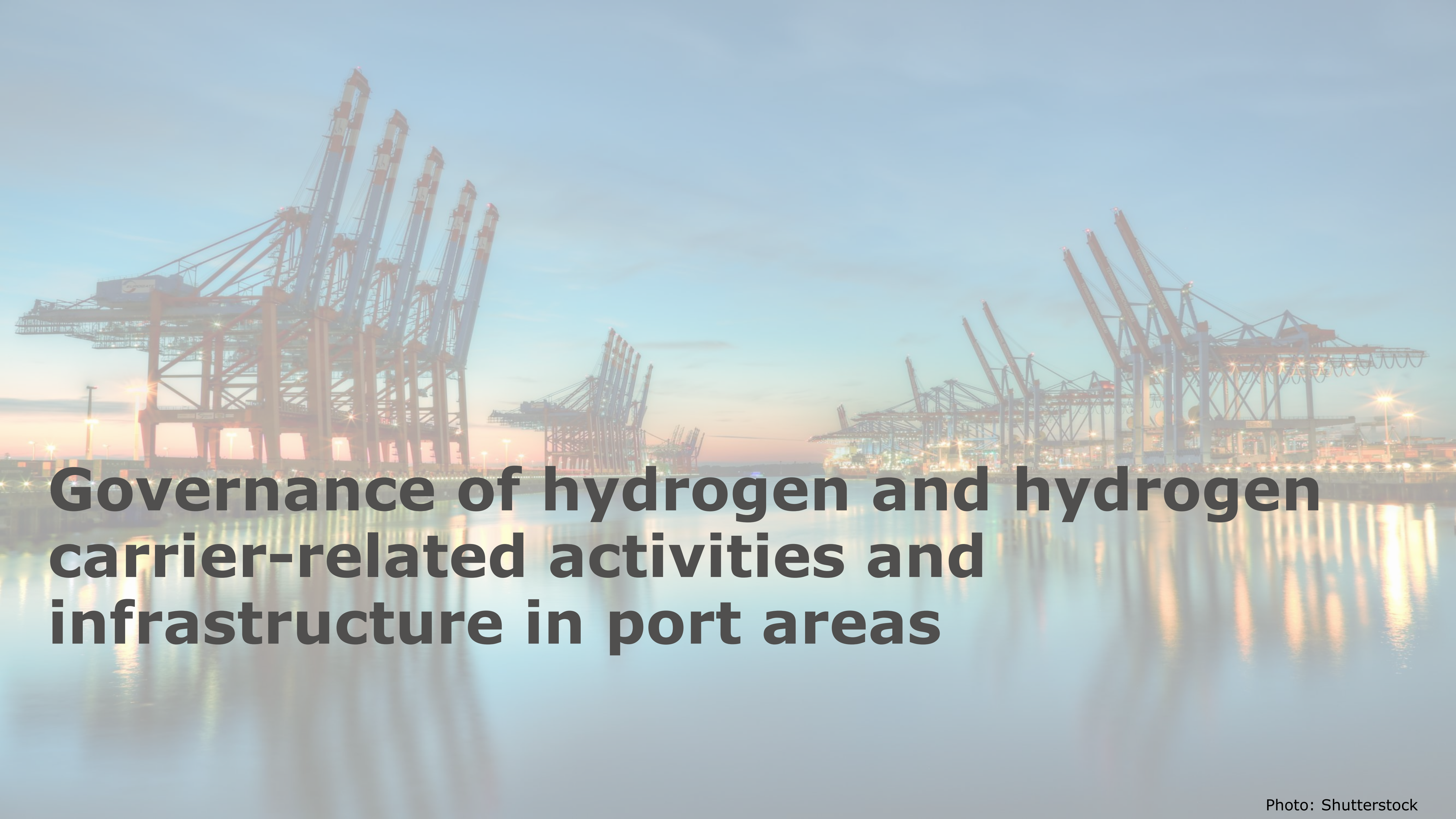
- **Create a one-stop-shop application process for project developers**, in such a way as to limit as much as possible the number of authorities involved in the entire administrative permit application and granting process (Article 12)
- **Stimulate the implementation of participatory approaches** that involve port-related stakeholders, local and regional authorities, civil society, non-government organizations and energy communities, thus enhancing public acceptance and engagement and facilitating the timely realization of locally adapted investments in hydrogen-related infrastructure in port areas (Article 8)[2].
- **Establish clearly defined, accelerated and as short as possible deadlines for all the steps required for the granting of permits** to build and operate renewable (hydrogen) energy projects (Article 3)[3].

Ensuring EU long-term industrial and technological leadership in hydrogen-related technological applications in port areas

- **Development of competitive technical expertise and industrial know-how in hydrogen-related technological applications in the maritime sector.** Recognizing the EU maritime industry as a strategic sector for the EU and building on the solid European position in building complex ships and manufacturing the required maritime equipment, systems, and technologies, the European Commission and Member States should ensure that technical expertise and industrial know-how of the EU maritime ecosystem develop and maintain a competitive advantage on hydrogen-related technological applications in the maritime sector.
- **Development of a skilled workforce.** Building on the highly professionalized and skilled EU maritime industry workforce, the EU could strengthen its efforts to ensure that a sufficient number of qualified personnel, particularly in technical and STEM fields[4], develop the necessary skills to design, implement and deliver hydrogen-related infrastructure projects in port areas. In that respect, the large project launched by ERASMUS+ and the Clean Hydrogen Partnership on addressing shortage of skills in the hydrogen economy could support specific actions in the maritime sector. Further, the European Pact for Skills could support Member States and private stakeholders in urgently stepping up their efforts and investment in the development of reskilling and upskilling programmes in port areas.

Notes: (1) Lessons can be learned from Germany's LNG Acceleration Act (May 2022), which was implemented as a matter of urgency to simplify permitting procedures for LNG terminals and associated facilities. With the enforcement of this Act, permitting procedures, which would normally have taken up to a year, have been reduced to only a few days (see Taylor Wessing, 2022); (2) Such an approach should be particularly prominent in permitting procedures for infrastructure historically subject to negative public perception, such as the construction of ammonia storage facilities and other ammonia-related infrastructure (e.g., import terminal, pipeline); (3) For instance, Member States should establish binding maximum deadlines for all relevant stages of the environmental impact assessment procedure; (4) Science, Technology, Engineering and Mathematics; (5) Modelled on the European Battery Alliance Academy, the Commission announced in February 2023 that it will propose to establish Net-Zero Industry Academies to roll out up-skilling and re-skilling programmes in strategic industries for the green transition, such as raw materials, hydrogen and solar technologies (see A Green Deal Industrial Plan for the Net-Zero Age, 2023). **Sources**: COM(2022) 591 final; COM(2022) 230 final; C(2022) 3219 final.

Gap analyses and recommendations on areas of priority for R&I projects, safety-related regulations, codes and standards and non-technical (policy, regulatory, strategic, governance, investments, etc.) provisions



Governance of hydrogen and hydrogen carrier-related activities and infrastructure in port areas

Photo: Shutterstock

Introduction: Governance of hydrogen and hydrogen carrier activities in port areas as a precondition to the development of hydrogen and hydrogen carrier activities

Description of the activity: Institutional and organisational structure defining and governing the development of hydrogen and hydrogen carrier-related activities and initiatives in each port ecosystem and coastal area.

Context and background

- The rollout of the EU Commission's REPowerEU plan will be achieved to some extent by improving domestic production and (non-EU) supply of renewable hydrogen and hydrogen carriers, which requires large-scale production and import infrastructure as well as new hydrogen transport corridors across Europe.
- Although port activities have traditionally been associated with facilitating the arrival and departure of ships, the use of berths, sheds and loading facilities, and the unloading, storage and distribution of goods, the **acceleration of the energy transition will increasingly have a profound impact on ports areas**, as they are natural gateways for energy flows to European industries, transport systems and households.
- In this context, **port areas can facilitate the energy transition** by delivering and/or using affordable renewable/low-carbon hydrogen or hydrogen carriers and by connecting production/import, storage, and transportation infrastructure.
- **Given that the development of these new activities and infrastructure potentially requires significant long-term investments, robust, resilient and effective governance of hydrogen and hydrogen carrier activities in port areas is needed as a precondition to the efficient, rapid and large-scale development of hydrogen and hydrogen carrier-related activities**.
- The first collaboration initiatives, such as the Renewable Low Carbon Industrial Value Chain Alliance[1] and the European Clean Hydrogen Alliance[2], are being launched to bring together pubic and private stakeholders from across the hydrogen value chains with the common goal of maximizing cross-border cooperation towards the development of hydrogen-related activities in the European economy, including in port areas and the maritime sector.

Port of Antwerp[3]

Sources: (1) Renewable Low Carbon Industrial Value Chain Alliance; (2) European Clean Hydrogen Alliance ;(3) Port of Antwerp

Non-technical challenges associated with the development of efficient **governance** of hydrogen-related activities in port areas

Non-technical challenges hindering the efficient **governance of hydrogen and hydrogen carrier-related activities in port areas**:

1. **Lack of a more integrated approach to coastal energy planning encompassing all energy-related activities in a particular coastal area** (not limited by national borders[1]), and built on a set of specific spatial, climatic, technico-economic and societal parameters influencing where, when and how individual port areas along a particular coastal area would undertake such energy-related activities (green corridor approach). **This barrier leads to a lack of coordination and cooperation between port authorities** (and other stakeholders such as shipowners, fuel producers, fuel suppliers, fuel transport operators and fuel users) along the same coastal area in developing hydrogen/hydrogen carrier activities.
2. **Lack of proper alignments between Member States' transport and energy strategies and policies**, which could lead to future discrepancies between the objectives that may be pursued by a port area for hydrogen-related activities and the energy strategy/policy developed by the respective Member State for the overall region.
3. **Lack of systematic consultation between the stakeholders of each maritime and inland port** to thoroughly assess the societal relevance and the technical-economic rationale for the development of hydrogen or hydrogen carriers-related activities in the port area[2].
4. **For sea and inland ports for which the development of at least one activity related to hydrogen or hydrogen carriers is assessed as positive or likely to be positive** in the coming decade (from a societal, economic and technical standpoint), there is a **lack of port-specific roadmaps**, developed in close collaboration between port authorities, future producers (importers) of hydrogen (carriers), storage infrastructure operators, transport companies and end-users in order to precisely define the key milestones (short, medium and long term), conditions (timing, quantities, end users, required infrastructure, investment needs, etc.) and responsibilities (as well as the interdependencies between them) for the successful integration of one or more hydrogen and hydrogen-related activities in the vicinity of the port[3]. This barrier can be divided in the following specific sub-barriers:
    - Lack of certainty about future demand for hydrogen and hydrogen carrier from industrial clusters (e.g., production of fuels, ammonia, primary steel) located in proximity to port areas, as well as from heavy-duty trucks operators.
    - Lack of clarity on the distribution of responsibilities for the development of various hydrogen and hydrogen carrier operations in port areas.
    - Lack of clarity as to which stakeholder(s) would be responsible for the safe coordination of day-to-day hydrogen (carrier) operations in ports.
5. **Lack of clear and harmonized regulatory frameworks for land use management in port areas**, resulting in multiple layers of competent authorities (e.g., fire authorities, port authorities, etc.) having different and conflicting interests or constraints with respect to the development of hydrogen or hydrogen carriers-related activities (i.e., import, bunkering, storage) in ports.

Notes: (1) So far, the responsibility of the development of energy-related activities is solely placed at the Member State level without systematic cross-border coordination/planning; (2) For instance: production, storage, bunkering, self use, distribution, etc.); (3) As of early 2023, a limited number of European ports, such as the Port of Rotterdam, the Port of Antwerp-Bruges or the Port of Hamburg, have already developed their port-specific roadmap that precisely defines key milestones, conditions and responsibilities for the development of hydrogen and hydrogen carrier activities in their port area.

Recommendations for addressing non-technical challenges related to the efficient **governance** of hydrogen-related activities in port areas (1/4)

Responsible authority(ies)**: Port authorities and other port stakeholders (1/2)**

1 Although the development of hydrogen or hydrogen carriers-related activities may not be technically feasible or economically relevant in the vicinity of many sea and inland ports, **port authorities should** engage with other relevant port-related stakeholders and **systematically assess the societal relevance and the techno-economic rationale for the development of hydrogen and/or hydrogen carriers-related activities and infrastructure in the port area**.

2 In view of enabling an efficient, rapid realization all the before-mentioned action streams, **port authorities should acquire and maintain a comprehensive understanding of the power and interest of all stakeholders who should be involved in the envisaged hydrogen-related activities in the port area**. In particular, port authorities should understand that the various stakeholders involved, sometimes with significant degree of influence on the decision-making processes, are likely to have individual interests to contribute (or oppose) to collaborative developments in hydrogen activities. The figure on slide 44 attempts to positioning the main relevant stakeholders for the development of port-related stakeholders in port ecosystem in a power-interest grid. While the degree of power informs on the influence of each stakeholder on the decision making, and thus on the realization of hydrogen-related activities in the port area, the degree of interest informs on the extent to which the stakeholder is interested in the realization of this activity in the port area. **Port authorities should prioritize targeting high-powered, low-interest stakeholders to at least secure their endorsemen**t, if not convince them of the associated benefits to play an active role in the development of green hydrogen projects in support of national and EU GHG emission reductions targets.

3 In those instances where the development of at least one hydrogen or hydrogen carrier related activity is assessed as positive or likely to be positive in the coming years, **port authorities should**, in line with the provisions of *Regulation 2017/352 (Art 15)*[1], **systematically consider setting up a hydrogen working group** composed of representatives of local authorities as well as private stakeholders operating in the port ecosystem (e.g., local industries, gas network operator, storage infrastructure providers, shipping companies, road transport companies, etc.).

4 In close collaboration with stakeholders represented in the hydrogen working group, **port authorities should develop a clear roadmap with key milestones** (short, medium and long term), **conditions** (timing, quantities, end users, required infrastructure, investment needs, etc.) **and organizational structure** (as well as the interdependencies between them) for the successful and safe integration of one or more hydrogen and hydrogen-related activities in the vicinity of their port[1]. Each port's own hydrogen roadmap must be aligned with their overall commercial strategy. Once the hydrogen roadmap is defined, the development of hydrogen projects and operations must be factored into individual port strategies and annual investment planning.

Note: (1) Regulation 2017/352 (Art 15): *"The managing body of the port shall, in accordance with applicable national law, consult port users and other relevant stakeholders on essential matters within its competence regarding: (a) the coordination of port services within the port area; (b) measures to improve connections with the hinterland, including measures to develop and improve the efficiency of (…) inland waterways transport; (c) the efficiency of administrative procedures in the port and measures to simplify them; (d) environmental matters; (e) spatial planning; and (f) measures to ensure safety in the port area (…)."*

Recommendations for addressing non-technical challenges related to the efficient **governance** of hydrogen-related activities in port areas (2/4)

Responsible authority(ies)**: Port authorities and other port stakeholders (2/2)**

5

Based on the port-specific stakeholders power/interest analysis (see recommendation 2), **port authorities should engage with the competent country-specific regulatory bodies to define a clear regulatory frameworks for land use management in port areas** that clearly allocates responsibilities among various authorities in a port areas for the development of hydrogen or hydrogen carriers-related activities (i.e., import, bunkering, storage) in ports.

6

Based on port's individual hydrogen roadmap, **coalitions or framework agreements should be developed between port authorities, key port stakeholders** (e.g., shipping companies, energy providers) **and nearby connecting ports**. Such a bottom-up approach is of particular importance to address the unique circumstances of each port (e.g., spatial, climatic, technico-economic and societal parameters) and facilitate the development of a more integrated (green corridor) approach to coastal energy planning through enhanced coordination and cooperation.

7

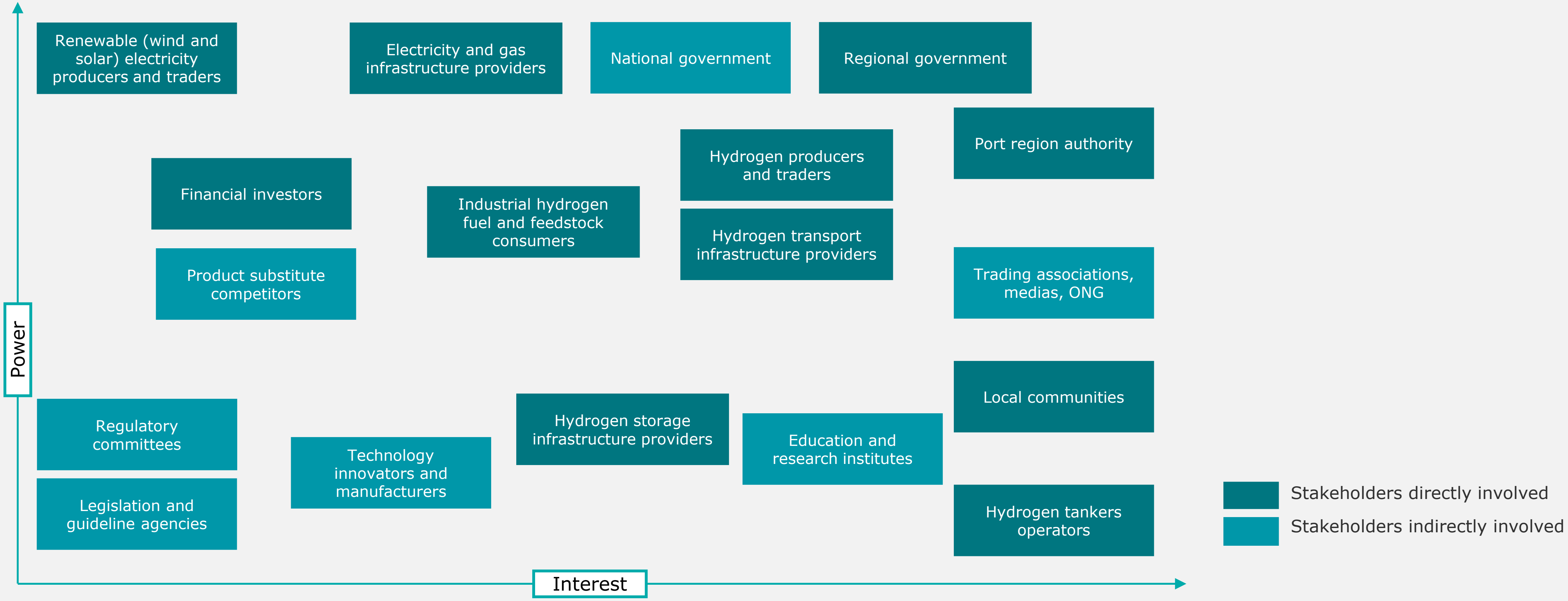
Within their existing governance structure (e.g., for ESPO, the Energy and Blue Growth Committee, the Sustainable Development Committee, the Intermodal and Logistics Committee and the Industry Committee), **ESPO and EFIP could**:

- **Provide guidance to the EU political legislator and Member State policy makers** on the specific regulatory provisions, policies and public investment programs (i.e., R&I, skills, etc.) needed to enable effective, rapid and large-scale development of hydrogen-related activities and infrastructure in maritime and inland port areas.
- **Maximize cross-border cooperation** (in compliance with the EU regulatory framework on competition) **between ports along a particular coastal area and hinterland waterway corridors** to 1) facilitate information sharing, knowledge exchange, and environmental risk reduction related to the development of hydrogen and hydrogen carrier activities and initiatives and 2) minimize divergent and conflicting interests between each port area.
- **Assist relevant port stakeholders** (e.g., port authorities) **in assessing the societal relevance and techno-economic rationale** for the development and successful integration of one or more hydrogen and hydrogen carrier activities in the vicinity of the port.
- **Provide guidance to port authorities on how best to inform local public debate and foster social and societal acceptance** of hydrogen and hydrogen carrier (particularly for ammonia) activities by stakeholders active in the vicinity of ports and nearby residential areas.

Note: (1) Ports could learn from the work conducted by some ports, such as the Port of Rotterdam, the Port of Antwerp-Bruges or the Port of Hamburg, which have already developed their port-specific roadmap that precisely defines key milestones, conditions and responsibilities for the development of hydrogen and hydrogen derivatives activities in the port ecosystem

Recommendations for addressing non-technical challenges related to the efficient **governance** of hydrogen-related activities in port areas (3/4)

Organizational structure defining and governing the development of hydrogen-related activities and initiatives in each port



■ Stakeholders directly involved
□ Stakeholders indirectly involved

Power-interest grid of direct and indirect stakeholders for hydrogen activities in port areas *(adapted from [Jepma et al., 2020])*

Recommendations for addressing non-technical challenges related to the efficient **governance** of hydrogen-related activities in port areas (4/4)

Responsible authority(ies): **EU Member States**

1 In line with regulatory provisions of the EU hydrogen policy framework (e.g., FuelEU Maritime, AFIR, TEN-T Regulation), **Member States should consider including specific provisions** (e.g., short-, medium- and long-term timelines and quantitative milestones, required infrastructure, investment needs, etc.) **in their respective national hydrogen strategy for the timely development of integrated hydrogen and hydrogen carrier infrastructure in the coastal areas under national jurisdiction**[1]. When defining the need for hydrogen and hydrogen carrier infrastructure in port areas, national hydrogen strategies should consider spatial integration of hydrogen infrastructure, local zoning and specific environmental regulations, as well as public, societal and local community acceptance. In areas where social and public acceptance concerns are likely to interfere with the foreseen increase in hydrogen and hydrogen carriers-related activities, strategies and associated actions (e.g., by involving local communities in project development) should be defined to minimize social and public opposition to the development of relevant infrastructure.

2 In the framework of their national hydrogen strategy, **Member States should consider promoting and facilitating greater regional coordination, integration and mutualization** (at the level of coastal areas) for the development of hydrogen or hydrogen carrier related activities and infrastructure (i.e., storage and distribution). To this end, Member States could work towards the **development of integrated cross-border hydrogen valleys involving several ports (maritime and inland)** located in different municipalities and provinces. In parallel, in regions hosting ports that may develop hydrogen or hydrogen carrier activities, Member States should ensure that related transport and energy strategies and policies are sufficiently aligned.

3 Emphasizing the additional freshwater needs associated with the enhanced roll-out of renewable hydrogen production[1], and considering the increasing pressure this water-intensive technology might place on freshwater supply, **Member States should ensure compliance with the EU Water Framework Directive in choosing the location for the roll-out of additional renewable hydrogen production capacities in the vicinity of ports**.

Note: (1) Understanding that port infrastructure are commercial assets, policy provisions developed by Member States should not specify requirements for infrastructure or activity development in specific port areas, but rather provide a clear and transparent national hydrogen vision and enabling policies to allow for the rapid deployment of hydrogen and hydrogen carrier related activities and infrastructure in domestic coastal areas; (2) Around 20 liters of water is needed per kg of green hydrogen produced.

Hydrogen and hydrogen carriers-related activities and infrastructure **in ports**

Import terminals of hydrogen and hydrogen carriers in EU ports

Photo: HySTRA

Introduction: Europe's major ports will be the gateway for importing hydrogen and hydrogen carriers by sea and will therefore need to provide terminalling infrastructure

Description of the activity: Providing terminalling infrastructure in ports for the safe offloading and handling of LH2 and hydrogen carriers (ammonia and LOHC), either at converted LNG terminals (if it is accepted that LNG terminals can be converted for use with LH2 or hydrogen carrier in the future) or at newly constructed dedicated LH2 and hydrogen carrier terminals.

Context and background

- With the deployment of the REPowerEU plan over the next decade, it is expected that **large quantities of LH2 and hydrogen carriers** (ammonia, methanol and LOHC) **will be imported into European ports by sea tankers**[1].
- Ports will have to play an active role in the development of this new international trade by **providing import terminals capacities** for LH2[2], ammonia[3], methanol and/or LOHC[4].
- Today, a typical European LNG terminal is a fixed onshore terminal[5] consisting of a jetty arm to transfer the LNG from the tanker into an insulated storage tank located at the terminal[6], a boil-off gas system including a compressor and re-condenser, high- and low-pressure pumps and piping, a vaporizer, a local pipeline that connects the terminal to the gas transmission grid as well as a control and measurement system.
- Ports will need to **plan appropriately for the safe offloading and handling** of LH2 or hydrogen carrier, **either at converted LNG terminals (if possible[7]) or at newly constructed (or extended) dedicated liquid bulk terminals**[8].

World-first LH2 tanker and import terminal in Japan (source: link)

Notes: (1) COM/2022/230 final; (2) Knowledge in building LH2 terminal storage is very scarce, as there is only one existing prototype liquid hydrogen terminal in Kobe, Japan, and the good is not globally traded; (3) Ammonia being a commodity already widely traded internationally via ships (there are already 88 import ports for ammonia worldwide), terminal infrastructure (including storage tanks) and handling know-how (including on safety aspects) are already widely developed; (4) Although conducted as a smaller scale (compared to ammonia), international transport of methanol and LOHCs via ships (chemical tankers) is also an activity already developed; (5) Floating LNG terminals (FSRUs-Floating Storage and Regasification Units) are also being developed, notably in Germany; (6) Import terminals often have more than one storage tank, typically two to four. Tanks make up 45-50% of the total LNG import CAPEX; (7) Although LNG terminals offer great advantages for becoming entry gates of hydrogen and hydrogen carriers into the EU (*located on the seaside, provide industrial-scale access to maritime logistics, have tanks with large storage capacities, have direct connection to the gas grid, are ready to work in cryogenic conditions, operators have profound experience in management of conversion and gas quality activities, most of the process technology and safety principles that relate to LNG import can also relate to LH$_2$ or hydrogen carriers import*), recent literature shows great uncertainties in the technico-economical feasibility of converting existing LNG terminals into LH2 or hydrogen carriers terminals. For instance, for LH2, most of the LNG terminal components need to be replaced, and the reuse is only possible for the components that have been constructed with hydrogen compatible materials (e.g., stainless steel 316L). For ammonia, although some components need to be replaced (pumps, piping), the conversion is seen as technically feasible and the economic impact on overall terminal cost is viewed as small; (8) Recent market developments and announcements suggest that ammonia may be the preferred career of hydrogen for long-distance sea transportation of hydrogen from exporting countries to the European economy.

Sources: ENTSOG, GIE and Hydrogen Europe, 2021; Fraunhofer ISI, 2022

R&I challenges and associated recommendations for the development of **liquid hydrogen import terminals**

Description of the R&I challenge: Terminals for unloading and storing LH2 consist of loading arms systems, tanks for storage, boil-off gas management system, cryogenic pumps and vaporizers for supplying gaseous hydrogen to pipelines and balancing purposes. Equipment and infrastructure used to handle LH2 at import terminals have been demonstrated at a very limited scale with the operation of the LH2 terminal prototype in Kobe (Japan). Hence, the different terminal components require scale-up for large-scale transport and/or adoption from LNG market for LH2 conditions. With storage tanks, boil-off-gas (BOG) management and rotary equipment being the most critical components.

Objective: **Design a large-scale LH2 receiving terminal in the order of those used for LNG today** (e.g., ~ 1000 kt per annum (ktpa) of LNG)

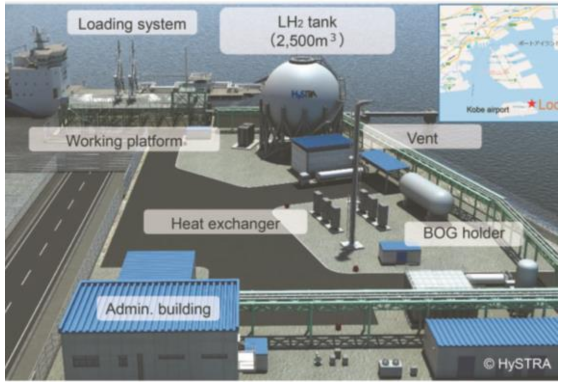
- **Target for 2030**: > 1000 tpd
- **Cost target for 2030:** < 2 €/kg*
- **Research Timeline**: 2023-2030

Where are we today: Japan’s Kawasaki Heavy Industries has completed construction work on the world’s first liquefied hydrogen receiving terminal for ships, the Kobe LH2 Terminal**. This terminal demonstrated the technical feasibility to handle shipped LH2 at small-scale and adopting loading arms from the LNG market.

Technical R&I aspects: LH2 terminal equipment and infrastructure would be exposed to cryogenic temperatures and would need to be designed to limit heat ingress as well as the risk of hydrogen embrittlement and permeability[1]. Hydrogen’s physical properties limit rotary equipment (compressors, expanders and pumps) to reciprocating equipment instead of conventional centrifugal configurations.

R&I projects should focus on:

- Scaling-up existing rotary equipment and/or developing alternative compression technology.
- Adopting equipment from LNG market (loading arms, vaporizers) for more severe temperatures, hydrogen embrittlement and leakage rates.
- Development of best-practices for boil-off gas mitigation and/or utilization (through temporary high pressure storage and subsequent pipeline injection or vessel vapor balancing).
- Detailed design, construction, and testing of a mid-scale ship receiving terminal (1000 tpd).



LH2 Terminal in Japan[2]

Recommendations:

- Member States and the EU could consider to **allocate public funding** to support the **design and construction of a large-scale LH2 terminal**.
- The EU should consider **providing financial support for conducting a comprehensive study that will clarify whether** (and if so, under what specific conditions) **it is technically and economically feasible to convert existing LNG terminals into LH2 terminals**.

Notes: (*) Total cost attributable to a hydrogen carrier system to supply, on average, 1000 tpd of hydrogen over a round trip distance of 3000 km, expressed on a per kg hydrogen delivered basis; (**) Project will establish a hydrogen energy supply chain using a liquefied hydrogen carrier of approximately 1/100 the capacity of a commercial scale.

Sources: (1) Development of Liquefied Hydrogen Terminal; (2) HYDROGEN SUPPLY CHAIN - HySTRA

R&I challenges and associated recommendations for the development of hydrogen carriers import terminals*

Description of the R&I challenge: Currently, ammonia is mostly used in fertilizer production and is thus already transported in large quantities. A global shipping infrastructure exists with a high maturity of storage, transport, and distribution technologies[1]. LOHC can be handled in conventional liquid bulk terminals due to similarities in physicochemical properties.

Where are we today: There are already 88 import ports for ammonia worldwide. OCI has made an FID for the expansion of its ammonia terminal from 400 ktpa to 1200 ktpa in the Port of Rotterdam[2]. In the same port, Air Products and Gunvor as well as Gasunie, HES International and VOPAK have announced the development of ammonia terminals[3,4]. Similarly, RWE has announced a 300 ktpa ammonia terminal in Brunsbüttel and Fluxys and Advario at the Port of Antwerp-Bruges[5,6]. Tank storage company Evos, Hydrogenious and Port of Amsterdam have announced to develop a 1 mtpa LOHC import terminal**,[7].

Technical R&I aspects: Ammonia import terminals store ammonia as a liquid at -33°C and atmospheric pressure in stainless steel tanks. Refrigerated storage at -33°C requires insulation and a boil-off gas system to mitigate heat ingress.

LOHC is a diesel-like substance and can easily be stored in conventional steel tanks.

R&I projects should focus on: Clarifying whether (and if so, under what specific conditions) it is technically and economically feasible to convert existing LNG terminals into ammonia or LOHC terminals.

OCI's ammonia import terminal in Port of Rotterdam (bordered by yellow line)[2]

Recommendation: The EU should consider **providing financial support for conducting a comprehensive study that will clarify whether** (and if so, under what specific conditions) **it is technically and economically feasible to convert existing LNG terminals into ammonia or LOHC terminals**.

Notes: (*) This analysis focuses on ammonia and LOHC as the main hydrogen carriers, other carbon-based fuels and solid carriers are relevant but outside the scope of this analysis; (**) Storage and distribution of LOHC at the liquid bulk terminal of Evos (rank storage company) requires only minor modifications.

Sources: (1) Innovation Outlook: Renewable Ammonia, 2022; (2) OCI; (3) Air Products and Gunvor; (4) ACE Terminal; (5) Fluxys and Advario; (6) RWE; (7) Evos, Hydrogenious LOHC Technologies and Port of Amsterdam.

Safety challenges and associated recommendations for the development of hydrogen or hydrogen carriers **import terminals in EU ports**

Description of the safety challenge: Inherently safe import terminals in EU ports contribute to the social acceptance of renewable energy sources.

Objective: **Development of safety regulations, codes, standards and protocols for hydrogen and hydrogen carrier import terminals**

Where are we today: There are no direct standards for import terminals of hydrogen and LOHC[1]. Ammonia and methanol are bulk chemicals shipped by ocean tankers for which receiving terminals are present. The IGF code (IMO MSC 95/22/Add.1) is the standard used for the shipping of gases and other low flashpoint fuels[2]. LNG, LH2, LOHC and ammonia terminals can co-exist. There is one existing liquid hydrogen prototype terminal in Japan.

Safety projects should focus on:

- Safety distances around the import terminal.
- External safety considerations for large scale storage of hydrogen carriers; position of venting lines during (especially) filling the storage facility.
- Considering the toxicity of ammonia and with that occupational safety, emission levels need to be minimized.
- Mechanical integrity and suitability of the materials in the various equipment used at different temperatures and pressures for liquefaction of ammonia, LH2 and LNG.
- Ways to reduce the boil-off in case of liquid hydrogen, as a small temperature increases causes a steep increase in pressure. Hence the flammable cloud formed in the atmosphere may pose a risk for both the facility and external safety (unless a re-liquefaction system is in place).

Liquefied Hydrogen Receiving Terminal in Japan[3]

Recommendations:

- **The EU** (through its most active/influential Member States) **should encourage the IMO to develop prescriptive harmonized international regulations as well as technical and safety standards** for **import terminals of hydrogen and LOHC**
- **The EU should support the development of testing and certification protocols** for **materials exposed to the various hydrogen carriers** and **materials in direct contact** (and experiencing frequent temperature swings) **with LH2**.

Sources: (1) European Clean Hydrogen Alliance, 2023; (2) Directive (EU) 2018/2001; (3) The port of Kobe, 2023

Non-technical challenges associated with the development of hydrogen or hydrogen carriers **import terminals in EU ports**

Non-technical challenges hindering the efficient, rapid and large-scale development of **hydrogen or hydrogen carriers imports terminals in EU ports:**

1. **Lack of specific roadmaps at the national and European levels** including key milestones, conditions and responsibilities (and the interdependencies that exist between them) **for the large-scale import of hydrogen and hydrogen carriers** (e.g., exporters, timing, quantities, infrastructure, investment needs, etc.).
2. **Lack of demand certainty** (i.e., willingness of potential end-users to purchase the imported green hydrogen or hydrogen carriers).
3. **Lack of supply certainty** due to an incomplete EU policy and regulatory framework to support the launch of an international market for hydrogen/hydrogen carriers (i.e., guarantee of origin/certification system so that imported hydrogen or hydrogen carriers can be accounted towards EU energy and climate targets, operational support mechanisms (i.e., Contracts for Differences) to allow early end-users to buy the first imported volumes, clear and rapid permitting procedures for the development of infrastructure, etc)[1].
4. **Lack of consensus on the fuel market with regards to the type of hydrogen or hydrogen carrier that will be preferred to import hydrogen** (e.g., ammonia, methanol, LOHCs, LH2), which delay stakeholders from making definitive decisions on which types of import infrastructure to develop[2].
5. **Lack of specific hydrogen or hydrogen carrier import pilot projects worldwide** encompassing broad public-industry partnerships (i.e., technology providers, investors, industrial consumers and logistics operators).
6. **Lack of available space in port areas** to build new hydrogen and hydrogen carriers import terminal infrastructure[3].
7. **Lack of adequate spatial and infrastructure planning and coordination** at the coastal area and national levels regarding the individual contribution of port-related stakeholders in the development of hydrogen and hydrogen carriers import infrastructure.
8. **Lack of EU and national CAPEX and OPEX funding support mechanisms** dedicated to the construction and operation of hydrogen or hydrogen carrier import terminals[4].

Notes (1) Also see slide 56; (2) Recent public announcements by relevant project developers show that ammonia appears as to be often considered as preferred option to transport green hydrogen over large distances via deep see tankers; (3) Today and for the years to come, it seems likely that LNG terminals (both the ones existing and the ones currently under construction) will need to be maintained as they are essential to ensure security of fossil gas supply to Europe. Therefore, given that space currently used by oil and LNG importing terminals are not expected to be freed up in the coming years/decades, additional liquid bulk (LH2 and hydrogen carriers) berths/(off)loading facilities will be required to augment and over time replace the fossil fuel imports; (4) Consideration should be given to the risk of unequal conditions of competition within the EU resulting from the provision of greater funding support by some Member States to attract hydrogen/hydrogen carriers imports to their own port terminals rather than to the port terminals of other EU Member States.

Recommendations for addressing non-technical challenges related to the development of hydrogen or hydrogen carriers **import terminals** in EU ports (1/4)

Responsible authority(ies)**: Port authorities and other port stakeholders**

1 **Port authorities of all major European seaports that could potentially host hydrogen or hydrogen carrier import terminals** (e.g., ports currently hosting LNG and ammonia import infrastructure, ports located nearby industrial clusters with already widely developed gas distribution infrastructure[1] and ports that are planed to be connected to the future European Hydrogen Backbone[2]) **should conduct technico-economic feasibility studies, the goal being to determine which European ports have the most appropriate spatial, technical** (i.e., pipelines, network infrastructure, etc.) **and socio-economic characteristics to host future hydrogen and hydrogen carrier import infrastructure in Europe**[3]. In particular, support should be provided to LNG importing ports in assessing the technico-economical feasibility of converting existing or future regulated LNG terminals into LH2 or hydrogen carrier (e.g., ammonia) terminals, taking into account the impacts on security of energy supply and climate objectives.

2 For those European ports that will be considered as meeting the technico-economic conditions to develop hydrogen or hydrogen carrier terminal infrastructure, **port-specific roadmaps that precisely define key milestones** (e.g., timing, quantities), **conditions** (e.g., imported fuel, required infrastructure, investment needs) **and responsibilities for the construction of terminal infrastructure should be developed** (in close collaboration with national governments).

3 In those Member States (such as Germany, the Netherlands or Belgium) that have clearly articulated in their energy policy framework their ambition to import hydrogen or hydrogen carriers from outside the EU, **port authorities could assist their national governments and the European Commission in establishing strong and resilient bilateral and/or multilateral strategic partnerships** with future hydrogen and hydrogen carrier exporting countries.

Notes: (1) For more information, see report 1 of the '*Study on hydrogen in ports and industrial coastal areas*' (link); (2) European Hydrogen Backbone, 2022; (3) Some leading European ports (i.e., Port of Rotterdam, Port of Antwerp-Bruges) are already conducting exploratory studies with more non-EU countries (e.g., Iceland, Portugal, Morocco, Oman, South Africa, Uruguay, Chile, Brazil, Australia and Canada) for the large-scale import of green ammonia.

Sources: Port of Rotterdam, Port of Antwerp-Bruges

Recommendations for addressing non-technical challenges related to the development of hydrogen or hydrogen carriers **import terminals** in EU ports (2/4)

Responsible authority(ies)**: EU Member States**

1. Given that converting some of the LNG terminal components for use with LH2 or hydrogen carrier is only seen as feasible if a concept for the conversion has been made in the construction phase of the LNG terminal and has been taken into account in the material selection of the terminal, **all future LNG terminals constructed in EU Member States should be designed and constructed considering later conversion to LH2 or hydrogen carriers**.

2. **Member States wishing to import hydrogen or hydrogen carriers should consider including in their national hydrogen strategy key milestones** (e.g., timing, quantities) **for the import of hydrogen or hydrogen carriers.** In particular these milestones should be complemented with short-term actions as well as a general national policy and regulatory framework enabling the large-scale import of hydrogen and hydrogen carriers to the country.

3. Given that the proximity of industry and distribution infrastructure can lead to benefits from process integration (e.g., to use cooling capacity from the cryogenic fluids or waste heat from industrial plants) and that the availability of distribution infrastructure to transport the hydrogen or hydrogen carrier after the imports is vital (e.g., a pipeline connection), **national governments should,** in the process of selection which ports is most suited to host future hydrogen or hydrogen carrier import terminals, **prioritize existing gas-import ports located in industrial hubs with already widely developed gas import and distribution infrastructure and/or ports that are planed to be connected to the future European Hydrogen Backbone**[1].

4. **The most pro-active Member States for hydrogen import and the selected port authorities should, as soon as possible, deploy specific hydrogen/hydrogen carrier import pilot projects**. These pilot projects should encompass broad public-EU industry partnerships in good cooperation with stakeholders from a broader ecosystem of EU technology providers, investors, industrial consumers and logistics operators.

Source: (1) European Hydrogen Backbone, 2022

Recommendations for addressing non-technical challenges related to the development of hydrogen or hydrogen carriers **import terminals** in EU ports (3/4)

Responsible authority(ies)**: The European Union (EU)**

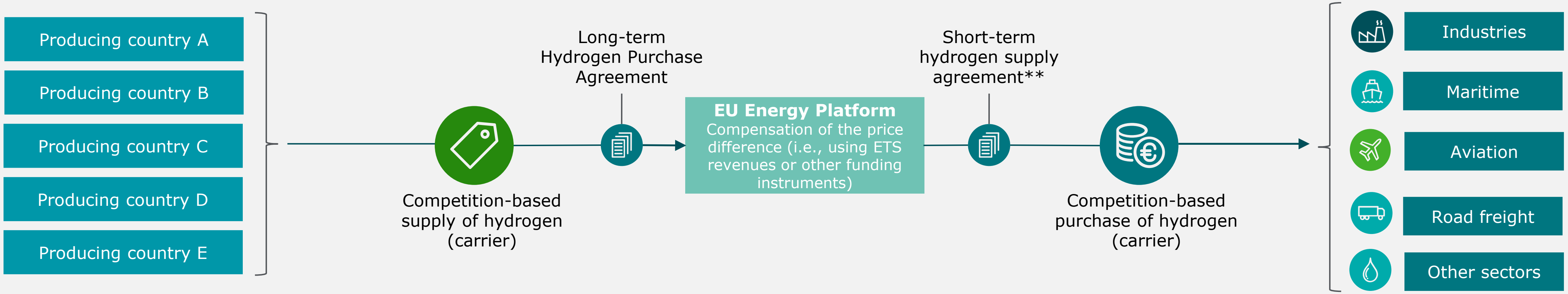
1 **The EU could establish** (e.g., through the Global European Hydrogen Facility and the EU Energy Platform), **a high-level roundtable between future potential hydrogen and hydrogen carrier exporters and EU countries** for the development of strong and resilient **international strategic partnerships as well as a joint hydrogen roadmap** with specific objectives, milestones, conditions and actions and the interdependencies between them. Such a roadmap should contribute to clarify mutual industrial benefits and provide certainty and accelerate the development of hydrogen import/export projects.

2 The EU should work toward **finalizing the EU policy and regulatory framework to support the launch of an international market for hydrogen/hydrogen carriers**. In particular, the development of a **common renewable and low-carbon hydrogen and hydrogen carrier certification system** (i.e., guarantee of origin) as well as an **operational support mechanisms** (e.g., Contracts for Differences) is a prerequisite to foster demand and supply certainties and encourage terminal infrastructure operators to launch appropriate investments.

Recommendations for addressing non-technical challenges related to the development of hydrogen or hydrogen carriers **import terminals** in EU ports (4/4)

Providing operational support at the EU level to foster the launch of international hydrogen import projects and encourage terminal infrastructure operators to timely make investment decisions: the example of contracts for difference

Even though, existing investment support mechanism (see slide 17) can accelerate the ramp up of the hydrogen economy across Europe (i.e., through funding of import terminals or pipelines), thereby also incentivizing imports, the EU **could provide further investor certainties by developing funding instrument dedicated to sustainable hydrogen** (as defined by the European Commission) **and hydrogen carriers imports at EU level**[1]. Indeed, a temporary effort to close the funding gap for selected hydrogen (carriers) import cases should contribute to provide the impetus to develop the import pathway. Therefore, **support measures such as short-term contracts for difference or carbon contracts for difference for European customers**, already known as an effective tool for deploying local renewable energy assets (wind, solar, etc.), **could be used to allow early off takers to consume the first necessary imported hydrogen (carriers) volumes**[2], in turn allowing non-EU hydrogen or hydrogen carrier suppliers **to secure long-term hydrogen purchase agreements**. For instance, **best practices can be drawn for the H2Global** (Germany) scheme, designed specifically for imports and which could serve as a blueprint for incentivizing imports to Europe[3].



Producing country A
Producing country B
Producing country C
Producing country D
Producing country E

Long-term
Hydrogen Purchase
Agreement

Competition-based
supply of hydrogen
(carrier)

EU Energy Platform
Compensation of the price difference (i.e., using ETS revenues or other funding instruments)

Short-term
hydrogen supply
agreement**

Competition-based
purchase of hydrogen
(carrier)

Industries
Maritime
Aviation
Road freight
Other sectors

EU centralized sustainable hydrogen import auction scheme *(adapted from the H2Global mechanism)*

Notes: (1) While the REPowerEU plan highlights the role of the Connecting Europe to Energy (CEF-E), the Recovery and Resilience Facility (RRF), and InvestEU in facilitating and securing funding for hydrogen import projects, none of these funding mechanisms provide explicit funding for international hydrogen projects; (2) From the demand side, it would be expected that future adjustments to the regulatory environment would increase buyers' willingness to pay, while an increasing number of suppliers could reduce the price. To capture these dynamics, contracts for difference are short-term; (3) The German Federal Ministry of Economics and Climate Action is providing the funding for the first H2Global window. As of today, €900 million is available to make up the difference between the hydrogen purchase agreement and the short-term hydrogen supply agreement. Additional funds of €3.6 billion are expected in the coming years[2].

Sources: H2Global, 2022; Energate messenger, 2022.

Bunkering of hydrogen and hydrogen derivatives

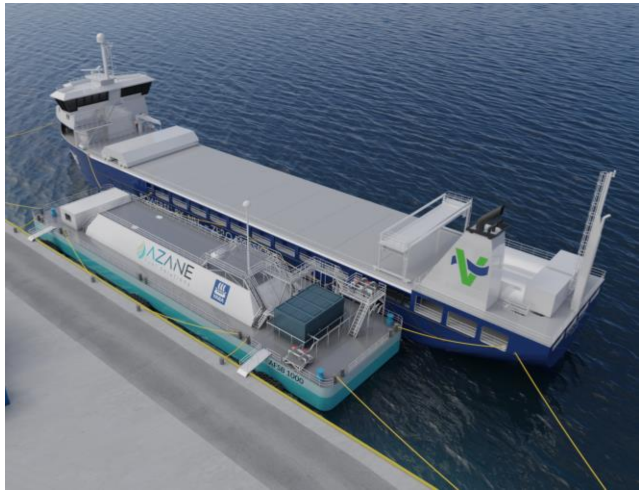
Photo: Shell

Introduction: Ports will need to timely develop hydrogen and/or hydrogen carrier bunkering infrastructure for maritime and inland shipping

Description of the activity: Bunkering of hydrogen/hydrogen carriers (i.e., ammonia, methanol) for use as fuel by ships, including *shore-to-ship* (fuel bunkered directly from a storage tank or pipelines), *ship-to-ship* (fuel bunkered from cargo tanks of a refueling vessel)[1] and *truck-to-ship* (fuel bunkered from a truck connected to the ship on the quayside)[2], but also floating ammonia bunkering systems and swappable compressed hydrogen (GH2) containers.

Context and background:

- With the final adoption of the FuelEU Maritime Regulation[4] and already adopted IMO targets[5] and Act of Mannheim[6] (inland EU shipping), the maritime sector is under increasing pressure to accelerate emissions reductions, notably through the gradual replacement of fossil-fuel powered vessels with low-carbon alternative fuels. In this context, while the uptake of specific low-carbon alternative maritime fuels is largely driven by shipping companies, **sea and inland ports can play a catalytic role in offering, promoting and using alternative maritime fuels**. Indeed:
    1. Firstly, while numerous alternative maritime fuels are being touted as the future of ships (i.e., compressed or liquid hydrogen, methanol, ammonia, synthetic fuels) and there is no clear answer as to which fuel or combination of fuels will be most prevalent, **ports have no choice but to already plan now in order to be in the position to provide the right fuels in sufficient quantities and in a timely manner**, while meeting the diverse and complex safety and handling requirements associated with these fuels.
    2. Secondly, **ports can also play a user role by using these alternative fuels to decarbonize their own port vessel fleet.**
    3. Thirdly, **ports can act as a promoter of alternative maritime fuels, notably by raising awareness** within the port community and wider public in order to push progress and direction of alternative fuel use and adoption in cooperation with relevant stakeholder.
- In this context, ports will eventually need storage facilities (see slides 95 to 104) from which bunkering infrastructure (i.e., vessels) will be able to source alternative fuels and supply them to ships that need them. In the case of small vessels based in ports, bunkering from a fixed barge may be another option[7].



Ammonia bunkering infrastructure protype by AZANE Fuel Solutions (Source: link)

Notes: (1) Ship-to-ship bunkering is most commonly used for seagoing vessels, as the supply vessel can be moored alongside the ship while it undergoes simultaneous cargo handling; (2) Truck-to-ship bunkering is most appropriate for smaller vessels, as volumes are small, and throughput is low; (3) Bunkering of GH2 in swappable containers integrates well with the existing logistics operations of inland navigation companies that handle containers. However, site safety requirements are required, and permits are needed. (4) In March 2023, the European Parliament and the Council reached an agreement on the FuelEU Maritime regulation to reduce the carbon footprint of Europe's maritime sector, including GHG reduction targets, a 2% target by 2034 for RFNBO uptake in the sector and a 2x multiplier until 2035 (allowing every ton of e-fuel used to be counted twice towards GHG savings) – for more information, see here; (5) The initial targets by the IMO are set to reduce carbon intensity of international shipping by 40% by 2030, and 70% by 2050 (compared to 2008). Moreover, the total annual GHG emissions need to be reduced by 50% compared to 2008 across international shipping; (6) To further improve the ecological sustainability of inland navigation, the Act of Mannheim (2018) tasked the Central Commission for the Navigation of the Rhine (CCNR) to develop a roadmap in order to reduce GHG emissions by 35% compared with 2015 by 2035, reduce pollutant emissions by at least 35% compared with 2015 by 2035 and largely eliminate GHG and other pollutants by 2050; (7) For smaller vessels, a distinct bunkering infrastructure may be required, given that they exhibit different physical compatibility and throughput rates than larger vessels (e.g., such as container ships).

R&I challenges and associated recommendations for the development of liquid hydrogen bunkering systems

Description of the R&I challenge: LH2 bunkering can be done using ship-to-ship, truck-to-ship, (floating) bunker stations and swappable tank-containers*. Existing technology for LNG can be adapted for handling LH2. The bunkering infrastructure for LH2 has to be developed which will require engineering, testing and qualification for different bunkering methods.

Objective: **Demonstration and qualification of LH2 bunkering**

- **Target for 2030**: 20 t H_2/h**
- **Cost target in 2030**: NA
- **Research Timeline**: 2023 - 2030

Where are we today: HySHIP project to validate LH2 supply chain in port areas[3]. Moss Maritime and partners have developed LH2 bunker vessel design[4]. Linde built and installed onshore and onboard hydrogen storage, distribution and safety equipment to supply LH2 to the MF Hydra[5].

Technical R&I aspects: Liquefied hydrogen is expected to be bunkered by means of a cryogenic pump with a flexible hose or arm transfer system[2]. Bunkering stations consist of two hose connections, one for the liquid hydrogen and one for the vapor return. The lower temperature of LH2 (vs LNG) requires pre-cooling the lines, prolonging the time needed for bunkering.

R&I projects should focus on:

- A qualification program for LH2 equipment shall be devised including: cryogenic mechanical testing; flow, burst and heat loss; quick disconnect and fall arrest.
- Adoption of bunkering equipment (loading arms) from the LNG sector for hydrogen application.
- Design studies for lay-out, thermomechanical studies for equipment and insulation performance.
- Numerical and experimental work to quantify the probability and occurrence and effects of incidents.
- Infrastructure deployment for facilities to store, handle, and distribute LH2 to ships, as well as equipment for transferring the fuel from the shore to the ship.

LH2 bunkering for MF Hydra through truck-to-ship[5]

Recommendation: The EU and/or Member States should consider to **allocate direct public funding** to pioneers in the EU port areas that are launching investments in R&I and market-ready projects aiming at demonstrating or decreasing the cost of **building and operating LH2 bunkering infrastructure**.

Notes: (*) The use of swappable containers for bunkering LH2 will not be preferred due to risks associated with hoisting (DNV – Report No. 10247894-2)

Sources: (1) Strategic Research and Innovation Agenda, 2022; (2) RH2INE DNV-GL Hydrogen Bunkering Scenarios; (3) About – HyShip; (4) Moss Maritime, 2019; (5) Linde to supply MF Hydra.

R&I challenges and associated recommendations for the development of compressed hydrogen bunkering systems

Description of the R&I challenge: Bunkering of compressed hydrogen to fixed tanks can be done from tube trailers (truck-to-ship), bunker station or hydrogen refuelling station for busses/cars with additional dispenser for ships[1]. The bunkering time is limited due to heating of the onboard storage tank. Alternatively, swappable containers with tubes or cylinders can be used reduce bunkering times and infrastructure requirements.

Objective: **Standardization and deployment of compressed hydrogen infrastructure**

- **Target for 2030**: 20 t H_2/h*
- **Cost target in 2030**: NA
- **Research Timeline**: 2023 - 2030

Where are we today: The FPS Maas is currently retrofitted wit a 1,2 MW fuel cell capacity fed by 2x500 kg swappable containers[2]. With Lloyd's Register approval a bunkering procedure has been developed and executed for shore-to-ship and truck-to-ship with 350 bar hydrogen[3].

Technical R&I aspects: Gaseous hydrogen can be transferred either by pressure balancing (with cascade filling) or by a compressor. When transferring hydrogen onboard, flow rate needs to be controlled to prevent adiabatic heating which could lead to softening or accelerated degradation of the fixed compressed hydrogen tank[2]. Experience gained from previous development of compressed hydrogen refuelling systems for other modalities will be relevant, but faster filling and larger volumes are required for ships.

R&I projects should focus on:

- Develop solutions (equipment and fuelling procedures) to increase bunkering time by mitigating fixed fuel tank temperature increase.
- Standardisation of engineering solutions and fuelling protocols.
- Development of a multi-modal, stationary refuelling solution.
- Infrastructure deployment in corridor for facilities to store, handle, and distribute compressed hydrogen to ships.

FPS Maas, retrofitted inland container vessel with 2x 500kg compressed hydrogen in swappable containers[1]

Recommendation: The EU and/or Member States should consider to **allocate direct public funding** to pioneers in the EU port areas that are launching investments in R&I and market-ready projects aiming at demonstrating or decreasing the cost of **building and operating compressed hydrogen bunkering infrastructure**.

Notes: (*) Data taken from Strategic Research and Innovation Agenda (page 164);
Sources: (1) RH2INE DNV-GL Hydrogen Bunkering Scenarios; (2) Fleet – Future Proof Shipping; (3) Hydrogen bunkering procedure.

R&I challenges and associated recommendations for the development of **hydrogen derivatives (ammonia and LOHC) bunkering systems***

Description of the R&I challenge: Ammonia and LOHC bunkering can be done using ship-to-ship, truck-to-ship and (floating) bunker stations. Loading and unloading of ammonia from terminal to ammonia-carrying ships is currently handled safely in ammonia bulk transfers[2]. LOHC can utilize existing bunkering infrastructure for diesel due to similarities in intrinsic qualities.

Objective: **Demonstration and qualification of LOHC and NH3 bunkering**

- **Target for 2030**: > 20 $tH_{2,equiv}/h^*$
- **Cost target in 2030**: NA
- **Research Timeline**: 2023-2028

Where are we today: Feasibility study to establish green ammonia ship-to-ship bunkering at the Port of Singapore[1]. The SABRE consortium has received approval in principle (AIP) from the US classification society ABS for an ammonia bunkering vessel design[2]. The Ship-aH2oy project has received €15m to demonstrate the operation of LOHC/SOFC system on the Edda Wind vessel[4].

Technical R&I aspects: Ammonia can be stored under pressure or refrigerated. Different arrangements of fuel tank and supply tank have specific bunkering equipment requirements. Pressurized fuel tanks can be bunkered both by pressurized and refrigerated tanks[2]. For the bunkering of ammonia, toxicity is the main risk[3].

R&I projects should focus on:

- A qualification program for ammonia equipment.
- Infrastructure deployment for facilities to store, handle, and distribute ammonia to ships, as well as equipment for transferring the fuel from the shore to the ship.
- Numerical and experimental work to quantify the probability and occurrence and effects of incidents.
- Demonstrate LOHC bunkering with existing bunkering infrastructure.

Ammonia bunker vessel[5]

Recommendation: The EU and/or Member States should consider to **allocate direct public funding** to pioneers in the EU port areas that are launching investments in R&I and market-ready projects aiming at demonstrating or decreasing the cost of **building and operating ammonia and LOHC bunkering infrastructure**.

Note: (*) This analysis focuses on ammonia and LOHC as the main hydrogen carriers, other carbon-based fuels and solid carriers are relevant but outside the scope of this analysis; (**) Data taken from Strategic Research and Innovation Agenda (page 164) equivalent amount for NH3 and LOHC to provide same energy content

Sources: (1) Maersk to offer ammonia bunkering in Singapore - Maritime Gateway; (2) DNV GL Ammonia as a marine fuel; (3) DNV-GL QRA of liquid ammonia bunkering; (4) Ship-aH2oy first-of-its-kind maritime LOHC; (5) Maritime Executive, 2022

Safety challenges and associated recommendations for the development of alternative fuels bunkering infrastructure for maritime and inland shipping

Description of the safety challenge: The handling and bunkering of all hydrogen-based maritime fuels (like gaseous hydrogen, (cryo)compressed hydrogen, liquid hydrogen, ammonia, methanol, liquid organic hydrogen carriers, metal hydrides) in a port environment are associated with potential safety hazards (explosion, fire, toxicity) that can have an immediate impact on the physical safety of people, building structures and equipment in the direct proximity.

Objective: **Development of a set of safety regulations, codes and standards for enabling safe hydrogen-based fuel bunkering activities in a port environment.**

Where are we today: Bunkering guidelines, procedures, standards and checklists for bunkering of hydrogen-based fuels do not exist[1]. CEN/CENELEC are in the early stages for developing standards for bunkering hydrogen[2]; some generic inputs can be retrieved from Norwegian standard FOR-2009-06-602 (does not cover hydrogen)[3]. Experience with the loading and unloading of sea going vessels carrying methanol and ammonia is available. Although different from bunkering, overlap in lessons learned are to be considered[4].

Safety projects should focus on:

- Assessment of the cyclic thermal effects on durability and integrity of storage tanks and hoses during direct gaseous hydrogen fueling; design considerations and integrity of hoisted (swappable) fuel containers to survive unintentional drops from the swapping cranes.
- Ventilation considerations in terms of position of vent pipes relative to living quarters and height above deck; installation of gas detectors in fresh air ventilation to accommodation and working spaces.
- Firefighting systems appropriate for hydrogen carrier used and fire loads anticipated; fire integrity of the fuel tank; fire detection systems and their measurement locations.
- The location of the bunkering infrastructure in relation to the safety distance required; distances differ per phenomenon - toxicity (ammonia), overpressure (explosion) and heat radiation (explosion/fire); Determination of scale of the operations in light of the more stringent guidelines of SEVESO III (5 tonnes limit).

Recommendations:

- See recommendation 3 page 64
- See recommendation 1 page 65
- See recommendation 2 page 65

Sources: (1) WPSP, 2023; (2) European Clean Hydrogen Alliance, 2023; (3) RH2INE Kickstart Study, 2022; (4) Van Hoecke et al., 2021

Non-technical challenges associated with the development of **alternative fuels bunkering infrastructure for maritime and inland shipping**

Non-technical challenges hindering the efficient, rapid and large-scale **development of alternative fuels bunkering infrastructure for maritime and inland shipping:**

1. **Lack of port-specific roadmaps/planning developed by port authorities** in collaboration with future hydrogen (derivatives) bunkering fuel companies, alternative fuel storage owners, terminal operators and shipping companies **to precisely define governance**, **as well as key milestones and conditions for the development of alternative fuel bunkering activities** in ports (i.e., timing, quantities, end-users, required infrastructure, investment needs, etc.).
2. **Lack of consensus on what will be the future fuels mix of choice in the maritime sector** (e.g., ammonia, methanol, e-fuels, LH$_2$, GH2), preventing hydrogen and hydrogen carrier bunkering infrastructure from moving from the R&D phase to wider adoption.
3. With the likely expansion of several alternative marine fuels in the coming years, various bunkering options with different technological requirements will be needed[1]. This situation may lead to incre**ased pressure in ports that are already facing land scarcity, as separate bunkering installations require more and different berthing points, and large safety zone requirements may be needed** for at least some of these alternative fuels (e.g., ammonia)[2;3].
4. **Lack of sufficient demand and supply** (availability of alternative maritime fuels in ports in sufficient quantities) **certainties** for hydrogen/hydrogen carriers-based bunkering fuels to incentivize seaports (i.e., terminals, bunker operators and/or other third parties to invest in dedicated bunkering infrastructure (e.g., filling points and bunker barges).
5. **Lack of EU-wide harmonized technical and safety protocols**, as well as regulatory framework (including clear guidelines to Member States on administrative practices and permitting procedures) for the construction and safe operation of hydrogen and hydrogen carriers bunkering infrastructure in the shipping sector.
6. **Lack of harmonized operational practices between Member States for ship bunkering**, resulting in the need to design and build several types of bunkering infrastructure for each (alternative) maritime fuel, adapted to the bunkering specificities of the Member States.
7. **Lack of innovation breakthroughs to further improve the efficiency and safety in handling and bunkering alternative fuels.**

Note: (1) For instance, while LH2 requires highly insulated containers with cryogenic hoses for bunkering, ammonia is corrosive and toxic and need specialized equipment to eliminate any potential for leakage. Even though battery-electric propulsion seems to display great viability for inland vessels or port support vessels, innovative bunkering solutions such as containerized fuel tanks for GH2 enables simplified bunkering and can initiate the use of hydrogen in inland shipping; (2) While an adequate dedicated area for fuel handling and bunkering would be required for all alternative maritime fuels, the bunkering of ammonia is expected to need substantially larger safety distances around locations where ship-to-ship bunkering takes place than GH2, LH2 or methanol; (3) Additionally, given that energy density of alternative maritime fuels are substantially less per volume than traditional fossil fuels, more space is required on top of the additional space needed to adhere to safety distances.

Recommendations for addressing non-technical challenges related to the development of **alternative fuels bunkering infrastructure** for shipping (1/2)

Responsible authority(ies)**: Port authorities and other port stakeholders**

1 As the adoption of alternative marine fuels becomes more widespread, **all port authorities with bunkering operations in their ports need to consider how best to develop bunkering infrastructure for alternative fuels**, either by taking on this responsibility themselves or by using third-party bunkering services in their port. To do so, under the leadership of port authorities, **port areas** (terminal operators, alternative fuel storage owners, fuel/bunker production company and shipping companies) **should define a framework** (e.g., governance, timing, quantities, end-users, required infrastructure, investment needs, space availability etc.) **for the development of alternative maritime fuels bunkering infrastructure** that promotes and drive supply and demand dynamics of these fuels.

2 If **port authorities** not directly responsible for the development and operation of alternative fuel bunkering infrastructure, they **should actively contribute to encouraging, stimulating, or compelling** (depending on port governance and regulatory powers) **private fuel bunkering operators to timely develop and operate alternative fuel bunkering infrastructure**. For instance, This incentivization can be done by:

- **Altering regulatory frameworks**, **providing guidance** (i.e., in coordination with relevant societies and associations), or including specific provisions in tender specifications or terminal concession contracts.
- **Investing in specific flagship demonstration projects** to prove the technical and economic feasibility of safely handling and bunkering alternative fuels.
- **Providing support to identify and secure access to European and/or national public funding programmes**.
- **Providing training support for personnel of bunkering operators** on the safely operation and maintenance of alternative fuel bunkering infrastructure.

3 Pending the development of IMO and ISO technical standards, **relevant stakeholders** (e.g., classification societies and associations), **could align themselves to establish harmonized technical and safety standards,** as well as **guidelines, procedures and checklists** for **bunkering of alternative maritime fuels as well as technological standards for building alternative maritime fuel bunkering infrastructure and equipment** used in Member States.

4 Due to the spatial requirements of building and operating the various bunkering infrastructure associated with the likely expansion of several alternative maritime fuels, **sea and inland ports with space limitations may be able to bypass their own alternative bunkering requirements by contracting with larger ports or nearby alternative fuel providers for bunkering of specific fuels**. In turns, ports could also consider to specialize in specific alternative maritime fuels that will also supply other ports in the same coastal area.

Recommendations for addressing non-technical challenges related to the development of **alternative fuels bunkering infrastructure** for shipping (2/2)

Responsible authority(ies)**: The European Union (EU) and Member States**

1 Building on the lessons learned from the experiences of bunkering LNG as a fuel for ships, as well as on the wide range of best practice publications developed by relevant stakeholders (e.g., classification societies), **the EU** (through its most active/influential Member States[1]) **should encourage the IMO to develop prescriptive harmonized international regulations, clear guidelines on administrative practices and permitting procedures**, as well as technical **and safety standards** (e.g., on issues such as safe loading and unloading of ships while bunkering, standardization of connectors, methane slip, etc.), **for the bunkering of hydrogen and hydrogen-based fuels**. In parallel, **the EU should encourage the International Organization for Standardization to revise the relevant international ISO standards and guidelines**.

2 Building on future updated IMO regulatory framework for the bunkering of hydrogen and hydrogen-based fuels, **the EU should work with the relevant regulatory and standardization authorities** (i.e., CESNI, CCNR) **to develop prescriptive harmonized EU-wide regulations, clear guidelines to Member States on administrative practices and permitting procedures, as well as technical and safety standards for building and operating hydrogen and hydrogen-based fuels bunkering infrastructure in inland ports**. This regulatory development is critical (along with the large-scale uptake of battery-powered ships) to ensure that the 2030 market-ready zero-emission ships target of the Smart and Sustainable Mobility Strategy (2020) is reached.

Note: (1) Given that the European Commission is only an observer member of the IMO, EU Member States that are the most active and influential within the IMO could steer the discussions and negotiations in favor of the development of harmonized bunkering technical and safety standards as well as a regulatory framework for licensing and authorizing bunkering infrastructure (i.e., clear guidelines on administrative practices and permitting procedures) for alternative maritime fuels.

Use of hydrogen and hydrogen-based fuels in the maritime sector

Photo: HydrogenFuelNews

Introduction: Hydrogen and hydrogen-based fuels offer great potential for the maritime sector and can significantly contribute to decarbonization

Description of the activity: Use of hydrogen (compressed or liquid form) or hydrogen-based fuels (ammonia, methanol, e-fuels) as a fuel in maritime activities, both in deep-sea and short-sea applications, as well as in inland navigation activities.

Context and background:

- Energy-dense oil fuels now account for almost all of the fuel burned in maritime engines. In 2018, the IMO adopted its initial GHG emissions reduction strategy (to be updated in 2023), which sets targets to reduce the carbon intensity of international shipping by at least 40% by 2030 (with continued efforts to reach 70% by 2050) compared to 2008 and to reduce total annual GHG emissions from international shipping by at least 50% by 2050 compared to 2008[2]. **To meet the 2030 and 2050 targets, alternative (zero or low-carbon) maritime fuel vessels are urgently needed, as maritime vessels typically have a lifespan of more than 30 years[3].**
- Although no alternative maritime fuels are currently available on a large scale[4], **hydrogen and hydrogen-based fuels** (ammonia[5], methanol[6], e-fuels) **offer great potential for the maritime sector** and can significantly contribute to decarbonization and air pollution mitigation of the sector.
- As part of the EU Green Deal, **the EU has launched a range of legislation, regulations and initiatives to stimulate the development of alternative maritime fuels** in the maritime transport sector, such as:
  - **The FuelEU Maritime regulation**, which puts increasingly stringent limits on carbon intensity of the energy used by vessels from 2025, will increase the demand for sustainable alternative fuels in European shipping and ports.
  - **The revision of the EU Directive on the Deployment of Alternative Fuels Infrastructure**, which sets mandatory national targets for the deployment of alternative fuels infrastructure for vessels.
  - **The extension of the EU ETS to maritime shipping** with the aim of applying the "polluter pays principle" to the shipping sector and accelerating the transition to clean fuels[7].
  - **The revision of the Energy Taxation Directive (ETD)**, which no longer fully exempts fuels used for intra EU maritime transport from energy taxation.
  - **The Renewable and Low Carbon Fuels Value Chain Industry Alliance**, launched in 2022, which aims to stimulate the production and supply of renewable/low carbon fuels in maritime sectors[8].
  - **The Partnership Zero Emission Waterborne Transport** (ZEWT), which aims to deliver and demonstrate zero-emission solutions for all major ship types and services by 2030, enabling zero-emission waterborne transport by 2050[9].

Prototype of an ammonia-powered ship (source: link)

Notes: (1) Including tugboats, barges and vessels owned by port authorities or other port-related operators; (2) IMO GHG Strategy, 2018; (3) Hydrogen Europe (2021) based on data from Clarksons World Fleet Register; (4) Storing energy on board is for now the main challenge from a technical point of view (i.e., both hydrogen and other fuels that are made from hydrogen, such ammonia, e-LNG, e-methanol and e-diesel, have a much smaller volumetric energy density compared to traditional oil-based fuels); (5) Considered a promising option for larger ships, many challenges remain (low flammability, safety, N2O emissions and ammonia slip from the incomplete combustion) and burning ammonia in large internal combustion engines is still in the research and development phase (Hydrogen Europe, 2021); (6) Methanol is a carbon-based fuel (therefore, not carbon neutral unless the carbon is sourced from direct air capture) currently used by 11 tankers and one passenger ferry in Europe; (7) European Council, 2022; (8) RLCF Alliance; (9) ZEWT

R&I challenges and associated recommendations for the use of hydrogen as maritime fuel

Description of the R&I challenge: Hydrogen can be used in internal combustion engines (ICEs), fuel cells or hybrid configurations*. Fuel cells (PEMFC or solid oxide) have the advantage of very low levels of noise, vibration and pollutant emissions, higher energy efficiency (compared to ICEs**) and lower maintenance cost due to no moving parts[1]. In ICEs hydrogen can be the sole fuel (mono fuel) or used in a dual fuel system. ICEs are available at larger sizes, have a higher average power density, are more tolerant to load variations and have a longer lifetime[1]. Maritime applications require higher power and longer lifetimes than those developed so far by state-of-the-art fuel cells stack/systems. ICEs (duel and mono-fuel) are still in development[2,3,4].

Objective: **Testing and development of (dual fuel) H2 engines and large capacity fuel cells.**

- **Target for 2030**: fuel cells power rating: 10 MW; Maritime FCS lifetime: 80000h
- **Cost target for 2030**: PEMFC system capex: < 1000 €/kW
- **Research Timeline**: 2023-2030

Where are we today: The MF Hydra, a LH2 powered ferry, operates with two 200 kW fuel cells with above-deck LH2 tank[5]. HyShip project is collaborating on the design and construction of a new ro-ro demonstration vessel running on liquid green hydrogen (LH2)[6]. Hydrocat 48 operates with two MAN D28622 dual-fuel engines[7].

Technical R&I aspects: Hydrogen powered vessels require different vessel arrangements. FC's typically need battery electric storage systems to operate at optimum loads[8]. Hydrogen fuel containment systems can be installed either above-deck*** or below-deck in integrated structures[8]. Compressed hydrogen containment systems suffer from unfavorable gravimetric energy density whereas LH2 requires boil-off gas handling[8,9]. ICE development mainly concentrates on four-stroke (medium/high speed) short-sea applications with spark-ignited engines with low-pressure hydrogen admission and dual-fuel engines with low-pressure hydrogen and pilot fuel ignition[2].

R&I projects should focus on:

- Development of four-stroke dual fuel and hydrogen mono-fuel ICEs.
- Scaling up the power, efficiency (incl. heat integration), durability and operational performance of fuel cells design towards commercially relevant applications.
- Reducing CAPEX and OPEX of fuel cells systems for maritime applications.
- Integration of fuel equipment onboard large ships, modification of plants and ship architecture, and integrated control of hybrid power generation systems.


Norled MF Hydra, LH2 powered ferry[5]

Recommendation: Building on the Zero Emission Waterborne Transport (ZEWT) partnership and the Clean Hydrogen Partnership, the EU should continue to **allocate direct public funding to pioneers in the EU port areas that are launching investments in projects aiming at demonstrating** or **decreasing the cost** of **(dual fuel) hydrogen engines and large capacity fuel cells in inland and short sea shipping**, while considering **expanding fundings** in projects aiming for the construction **of large-scale vessels****.

Notes: (*) hybridisation of batteries, ICEs, fuel cells, etc; (**) Electrical motor for propulsion counteracts energy efficiency advantage; (***) Above deck installation benefits from natural ventilation against leaks; (****) Funding mechanisms complementary to the ZEWT partnership and the Clean Hydrogen Partnership (e.g., Innovation Fund) would be needed to support the construction of large-scale ocean-going vessels in the EU (e.g., large cargo vessels, large passenger vessels and long-route shipping vessels) (see SWD(2020) 331 final); **Sources**: (1) IRENA Global Trade Hydrogen; (2) MAN - Hydrogen in shipping; (3) Volvo Penta & CMB.TECH partner on dual-fuel hydrogen engines; (4) Wärtsilä - Future fuels in shipping; (5) Norled's hydrogen-powered HYDRA; (6) About – HyShip; (7) MAN dual fuel marine engine; (8) ABS hydrogen as marine fuel; (9) RH2INE Hydrogen Demand Scenarios.

R&I challenges and associated recommendations for the use of ammonia as maritime fuel

Description of the R&I challenge: Ammonia can be used in fuel cells, ICEs or hybrid configurations* but is not yet approved as a fuel by regulators and authorities[1]. In general, FCs have the advantage low levels of noise, vibration and pollutant emissions, higher energy efficiency (compared to ICEs) and lower maintenance. PEMFCs would require cracking of ammonia and is very sensitive to ammonia impurities[1]. SOFCs can convert ammonia directly but are not commercially available[1]. Internal combustion engines are considered in the near future in terms of cost, power density, load response and robustness but are likewise under development[1,2].

Objective: **Demonstrate and validation of ammonia for flexible fuel engines and fuel cells**

- **Target for 2030**: Ammonia fueled marine engine: > 10 MW, fuel cells power rating: 10 MW; Maritime FCS lifetime: 80000h
- **Cost target for 2030: fuel cells** system capex: < 1000 €/kW
- **Research Timeline**: 2023-2030

Where are we today: MAN Energy Solutions is developing a fuel-flexible, two-stroke ammonia engine as a key technology in the maritime energy transition[2]. Wärtsilä is coordinating the development of a four-stroke ammonia engine[3]. The Viking Energy will be retrofitted (under the ShipFC project) with a 2 MW solid oxide fuel cell capable of using ammonia and was awarded Approval in Principle by DNV[1,4].

Technical R&I aspects: Ammonia will impact the design of the engine, the fuel system, and general arrangements on and below deck[1]. PEMFC require on-board cracking, purification and FCs currently lack power density and load response capability**. Combustion of NH_3 and associated N2/H2 blends have not been investigated and might require additional technology to reduce NO_x and N_2O emissions. The toxicity of ammonia needs to be closely considered in the design of fuel containment and supply system. **R&I projects should focus on**:

- Design, testing and overall safety assessment of fuel containment and supply system for ammonia.
- Research on fundamental combustion physics, emission formation, ammonia slip, flame velocity and structure.
- Demonstration and validation of an ammonia-fueled marine engine.
- Ammonia cracker integration into the system without external power should allow a fully autonomous operation***.
- Scaling up the power, efficiency and operational performance of fuel cells designs towards commercially relevant applications.
- Integration of fuel equipment onboard large ships, modification of plants and ship architecture, and integrated control of hybrid power generation systems.

Viking Energy to be retrofitted with a 2 MW SOFC system[4]

Recommendation: Building on the Zero Emission Waterborne Transport (ZEWT) partnership and the Clean Hydrogen Partnership, the EU should continue to **allocate direct public funding to pioneers in the EU port areas that are launching investments in projects aiming at demonstrating** or **decreasing the cost** of **engines and fuel cells suitable for ammonia application in inland and short sea shipping**, while considering **expanding fundings** in projects aiming for the construction **of large-scale vessels******.

Notes: (*) hybridisation of batteries, ICEs, fuel cells, etc; (**) battery electric storage systems may be required to operate at optimum loads; (***) mostly relevant for PEMFCs which require high purity hydrogen to operate; (****) Funding mechanisms complementary to the ZEWT partnership and the Clean Hydrogen Partnership (e.g., Innovation Fund) would be needed to support the construction of large-scale ocean-going vessels in the EU (e.g., large cargo vessels, large passenger vessels and long-route shipping vessels) (see SWD(2020) 331 final). **Sources**: (1) Ammonia as a marine fuel DNV; (2) MAN - Ammonia engines; (3) Wärtsilä coordinates ammonia engine development; (4) Alma awarded Approval in Principle by DNV.

R&I challenges and associated recommendations for the use of LOHC as maritime fuel

Description of the R&I challenge: LOHC cannot be directly used in ICEs, fuel cells or hybrid configurations*. Instead, the LOHC requires dehydrogenation to release the hydrogen which is subsequently used as a fuel. The necessity to extract hydrogen from LOHC before it can be used as a fuel requires additional equipment (dehydrogenation unit) and for use in PEMFC would require an additional purification step. Purification is not needed in SOFCs. The dehydrogenation is an endothermic process and requires heat.

Objective: **Demonstration and validation of LOHC dehydrogenation in combination with fuel cells**

- **Target for 2030**: fuel cells power rating: 10 MW; Maritime FCS lifetime: 80000h
- **Cost target for 2030**: **fuel cells** system capex: < 1000 €/kW
- **Research Timeline**: 2023-2030

Where are we today: The Ship-aH2oy project has received €15m to demonstrate the operation of LOHC/SOFC system on the Edda Wind vessel[1].

Technical R&I aspects: LOHC requires an onboard dehydrogenation unit and due to the nature of the carrier require an additional fuel tank to store dehydrogenated carrier[2]. Most LOHCs have comparable physicochemical properties to diesel and are non-toxic and inflammable[2]. LOHCs can be stored at ambient conditions in standard steel tanks. For SOFCs the high-temperature heat could be integrated into the dehydrogenisation process[2]. Due to the low-pressure release of the LOHC, compressors are required if the fuel system requires pressurised hydrogen[2]. Direct conversion of LOHC in a fuel cell is still in the early phase of development[3].

R&I projects should focus on:

- Development of direct conversion LOHC in fuel cells.
- Integration of LOHC dehydrogenation unit into the system without external power allowing fully autonomous operation.
- Scaling up the power, efficiency and operational performance of fuel cells designs towards commercially relevant applications.
- Integration of fuel equipment onboard large ships, modification of plants and ship architecture, and integrated control of hybrid power generation systems.

Ship-aH2oy project aims to install a SOFC with integrated hydrogen release unit[1]

Recommendation: Building on the Zero Emission Waterborne Transport (ZEWT) partnership and the Clean Hydrogen Partnership, the EU should continue to **allocate direct public funding to pioneers in the EU port areas that are launching investments in projects aiming at demonstrating** or **decreasing the cost** of **fuel cells in combination with LOHC dehydrogenation in inland and short sea shipping**, while considering **expanding fundings** in projects aiming for the construction **of large-scale vessels****.

Note: (*) hybridisation of batteries, ICEs, fuel cells, etc; (**) Funding mechanisms complementary to the ZEWT partnership and the Clean Hydrogen Partnership (e.g., Innovation Fund) would be needed to support the construction of large-scale ocean-going vessels in the EU (e.g., large cargo vessels, large passenger vessels and long-route shipping vessels) (see SWD(2020) 331 final).

Sources: (1) Ship-aH2oy first-of-its-kind maritime LOHC ; (2) MariGreen - Hydrogen Feasibility Study; (3) Partnership to develop fuel cell with (LOHC).

Safety challenges and associated recommendations for the use of hydrogen and hydrogen carriers as shipping fuel (international and inland shipping)

Description of the safety challenge: The external safety implications of ships at especially mooring locations and the risks to the ship's crew members.

Objective: **Supplementing the applicable European standards to include hydrogen and hydrogen carriers.**

Where are we today: For the construction requirements of inland shipping vessels ES-TRIN (European Standard laying down Technical Requirements for Inland Navigation vessels)[1] is applicable, which is being expanded to include fuel systems based on hydrogen and hydrogen carriers by CESNI. The police regulations for the navigation of the Rhine (RPR) from the CCNR (Central Commission for the Navigation of the Rhine) are being adapted to allow vessels to use hydrogen as fuel. The EU-directive on the deployment of Alternative Fuels Infrastructure (AFID) (2014/94/EU)[2] and the Renewable Energy Directive (RED II) 2018/2001/EU[3] are touching this subject, but not specifically. EU Directive 2009/16 promotes the use of alternative fuels. Methanol is currently used by 11 tankers and one passenger ferry in Europe.

Safety projects should focus on:

- The location of the storage tank on the ship with respect to the safety of the personnel; for liquid hydrogen / ammonia this is supplemented with the location of the vents (boil-off) and ventilation in relation to both personnel and external safety.
- The development of low volume safety barriers around the onboard storage facilities from the rest of the equipment.
- With ammonia, the tuning of the engines (direct combustion) such that there are no emissions of ammonia to the environment, especially at cold start.
- The mechanical integrity of storage tanks in relation to crash scenarios of the ships.
- Development of new, higher pressure (700+ bar) composite tanks to extend the range of the inland navigating vessels.
- Development of internal conversion technologies to convert hydrogen carriers (LOHC, hydrides, ammonia) in-situ to hydrogen for increased safety and extended range; specific attention needs to be paid to high temperature effects of the conversion technologies to the safety of the storage tanks (like enhanced boil-off for LH2).

Recommendations:

- See recommendation 4 page 73
- See recommendation 1 page 74
- See recommendation 2 page 74
- The EU should **support the development of testing and certification protocols for inland navigating vessels using hydrogen/hydrogen carriers as a fuel.**

Sources: (1) CESNI, 2019; (2) Directive 2014/94/EU; (3) Directive 2018/2001/EU

Non-technical challenges associated with the **use of hydrogen and hydrogen carriers as a fuel for international and inland shipping**

Non-technical challenges hindering the efficient, rapid and large-scale **use of hydrogen and hydrogen carriers as fuel for shipping:**

1. **Lack of clear and harmonized international and EU-specific regulatory standards and guidelines** (e.g., risk-based processes), as well as **administrative practices in the processes for building and operating (deep) sea/ocean-going and inland waterways maritime vessels powered by hydrogen (in a compressed or liquid form) or hydrogen-based fuels (ammonia, methanol, e-fuels)**, resulting in lengthy and costly procedures to obtain the administrative authorizations necessary to develop and operate these new vessels[1]. Note: Ammonia is considered a toxic product and is currently not permitted for use under IMO's IGF Code (*International Code of Safety for Ships using Gases or other Low-flashpoint Fuels*)[2] and IMO's IGC (*International Gas Carrier Code*)[3].
2. **Lack of sufficient alignment and collaboration between all the main value chain stakeholders** (i.e., renewable power generation, electricity grid, hydrogen production (and conversion), transmission and storage, hydrogen-based fuels bunkering, shipowners, shipbuilders) that need to be involved for hydrogen-based fuels to be used as a shipping fuel.
3. **Lack of sufficient certainty on the future availability and security of supply of hydrogen/hydrogen-based maritime fuels in ports** to incentivize maritime vessels producers to invest in the large-scale production of hydrogen/hydrogen derivatives-powered maritime fuels[4].
4. **Lack of economic competitivity of alternative hydrogen or derivatives maritime fuels compared to traditional oil-based maritime fuels**, leading to reluctance of maritime fuel users (e.g., vessels owners) to invest in the construction of vessels running on hydrogen or hydrogen derivatives fuels[5].
5. **Lack of consensus on what will be the future most economically competitive fuels mix in the maritime sector** (e.g., ammonia, methanol, e-fuels, LH$_2$, GH2) **for each type of shipping activity** (i.e., short and long distance, passengers ships, ferries, cargo ships, port vessels, etc.), resulting in high reluctance from shipowners to invest in vessels using alternative fuels, delaying hydrogen and hydrogen derivatives applications in the maritime sector from moving from the R&D phase to wider adoption.
6. **Lack of sufficient demonstration projects in European and national R&I programs** to demonstrate the use of hydrogen and hydrogen-based fuels as a fuel in the maritime transport sector.
7. **Lack of sufficiently qualified workforce for the operation of vessels running on hydrogen or hydrogen-based fuels.**

Notes: (1) In the absence of IMO regulation on how to build hydrogen fueled ships safely, classification societies have at their hand the use of well-established, risk-based 'alternative design' approval methodologies which have been used for alternative fuels to support shipowners. These classification societies approve the use of hydrogen fueled ships only if the safety, reliability and dependability of the alternative systems is demonstrated to be equivalent to that achieved with new and comparable conventional oil-fueled engine (source: Hydrogen Europe, 2021); (2) The IMO's IGF code provides mandatory criteria for the arrangement and installation of machinery, equipment and systems for vessels operating with gas or low-flashpoint liquids (mostly LNG) as fuel to minimize the risk to the ship, its crew and the environment. As of early 2023, discussions on whether and how to allow the use of ammonia as a maritime fuel are ongoing; (3) The IMO International Gas Carrier (IGC) Code, which regulates gases as a cargo, currently prohibits cargoes identified as toxic products (including ammonia) from being used as fuel for the carrying ship; (4) This barrier is of particular importance in the shipping sector as, given the very long lifespan of ships, ship owners are very reluctant to invest in the production of new ships using alternative fuels as long as they are not guaranteed sufficient demand for these ships in the long term, in order to avoid the risk of stranded assets; (5) At this stage, it seems that vessel owners are not sufficiently willing to bear the additional CAPEX and OPEX costs linked with building and operating ships propelled by hydrogen-based alternative fuels.

Recommendations for addressing non-technical challenges related to the **use of hydrogen and hydrogen carriers as a shipping fuel** (1/2)

Responsible authority(ies)**: Port authorities and other port stakeholders**

1 In line with the provisions of the FuelEU Maritime regulation and the revised EU Directive on the Deployment of Alternative Fuels Infrastructure (AFID), all port areas need to consider how best to gradually replace oil-based maritime fuels by alternative maritime fuels, both for inland/short sea and deep-sea ocean-going shipping applications. Under the leadership of port authorities and in close collaboration with alternative maritime fuel producers, shipping companies, vessels-owners, maritime fuel bunkering companies and fuel storage companies, **each port ecosystem should develop a port-specific roadmap** (e.g., governance, timing, type of fuel(s), conditions for use quantities, end-users, required infrastructure, investment needs, space availability etc.) **for the uptake of hydrogen and hydrogen-based maritime fuels in their areas**.

2 Under the framework of these port-specific roadmaps, port authorities, shipping companies, vessels-owners and fuel producers should **create coalitions agreements**, which could at a later stage expand to other stakeholders as well as connecting ports.

3 Port authorities should actively **contribute to encouraging and stimulating shipping companies and vessels-owners to timely shift towards maritime vessels powered by hydrogen and hydrogen-based maritime fuels.** This incentivization can be done by:

- **Facilitating joint agreements with shipping companies**, whereby, as demand for hydrogen or hydrogen-based fuels increases, the port will guarantee the provision of the appropriate fuel(s) and bunkering infrastructure as well as hydrogen or hydrogen-based maritime fuel at the port premises.
- **Altering regulatory frameworks** and **providing guidance** (i.e., in coordination with relevant societies and associations) to allow vessels powered by hydrogen and hydrogen-based fuels to call at the port's berth.
- **Incentivizing** calls by hydrogen-based fuels-powered vessels (e.g., by reducing port fees or fuel taxes, granting privileged access to docks or timeslots).
- **(Co-) investing in specific flagship demonstration projects** to demonstrate the technical and economic feasibility of using hydrogen fuel cells in tugboats, barges and vessels owned by port authorities (applications for which fuel cells using hydrogen appears as a promising zero-emission option)[1].
- **Facilitating the establishment of shipping manufacturing companies** specializing in the construction of new generations ships powered by hydrogen-based fuels in the vicinity of the port.

4 **Relevant stakeholders** (e.g., classification societies) **could align to develop one harmonized and simplified risk-based 'alternative design' approval methodologies** (currently being used to approve the use of hydrogen fueled ships pending the development of IMO technical regulations) to **allow quicker and less costly procedures** to obtain the required administrative authorizations to build and operate vessels powered by hydrogen(-based) fuels[2].

Notes: (1) Hydrogen Europe, 2021; (2) In September 2021 ABS published guidelines and requirements for the design, construction and survey of ammonia-fueled vessels

Recommendations for addressing non-technical challenges related to the use of hydrogen and hydrogen carriers as a shipping fuel (2/2)

Responsible authority(ies): **The European Union (EU) and Member States**

① Building on the lessons learned from the experiences of introducing LNG as a fuel for ships, as well as on the wide range of best practice publications developed by relevant stakeholders (e.g., classification societies), **the EU** (through its most active/influential Member States) **should encourage the IMO to finalize and enforce prescriptive international regulations, including clear guidelines to Member States on administrative practices and permitting procedures, as well as technical and safety standards for the utilization of hydrogen** (i.e., compressed and liquid hydrogen, including fuel cells) **and hydrogen-based fuels** (e.g., ammonia, methanol, e-fuels) **in deep-see and short-sea applications**. In particular, the **IMO IGC Code, IGF Code, ISM Code and the MARPOL Convention** (i.e., NOx Technical Code) **should be revised accordingly**. In parallel, **the EU should encourage** the ISO **to revise the relevant ISO standards linked to the aforementioned IMO's Codes**[1].

② Building on future updated IMO regulatory framework for the use of hydrogen and hydrogen-based fuels in deep-see and short-sea applications, **the EU should work with** the relevant regulatory and standardization authorities (i.e., **CESNI, CCNR) to develop prescriptive harmonized EU-wide regulations, including clear guidelines to Member States on administrative practices and permitting procedures**, **as well as technical and safety standards** for the **use of hydrogen and hydrogen-based fuels in inland waterway vessels**[2]. Considering that it is likely that small vessels in ports will be the first types of ships fueled by hydrogen or hydrogen-based fuels (i.e., via tube trailers and/or fixed compressed hydrogen tanks)[3], this regulatory development is critical (along with the large-scale uptake of battery-powered ships) to ensure that the 2030 market-ready zero-emission ships target of the Smart and Sustainable Mobility Strategy (2020) is reached.

③ EU and national policies and funding programs that aim at accelerating the decarbonization of the shipping sector should be **tailored to support the design, construction and retrofitting of zero-emission ships and associated equipment by EU companies over non-EU companies**[4].

Notes: (1) ISO standard 20519:2017, which complements the IGC Code and covers operational procedures, requirements for the LNG provider and requirements for the LNG facilities, with special attention paid to safety and fuel quality standards; ISO standard 18683:2015, which provides guidance on the minimum requirements for the design and operation of the LNG bunkering facility, including competences of the bunkering personnel and functional requirements for the equipment; (2) For inland vessels, Directive 2016/1629/EU empowers CESNI (Comité Europóen pour l'Élaboration de Standards dans le Domaine de Navigation Intérieure) to develop standards in the field of inland navigation; (3) Hydrogen Europe, 2021; (4) For instance, appropriate policy provisions should ensure that EU and public fundings aimed at developing hydrogen-related technological demonstration projects in the maritime sector support projects that are entirely conducted in Europe so that technical and technological capabilities built in the framework of these projects remain the ownership of European organizations.

Use of hydrogen and hydrogen carriers in cold ironing (onshore power supply)

Photo: Port of Rostock-Warnemuende

Introduction: In ports located in areas less suited to electrification, fuel cells or dual-fuel hydrogen internal combustion engines can provide energy to ships at berth

Description of the activity: Use of hydrogen or hydrogen carrier as a fuel in fuel-cell onshore power supply (OPS) systems (stationary or mobile) or dual-fuel hydrogen internal combustion engines, when direct electrification is not the most cost-efficient decarbonization pathway[1].

Context and background

- Vessels require power when they are docked for on-board activities and at night. Usually, this electricity is produced by the ship's onboard diesel engines. However, in a context where European ports and shipping companies are required to improve the overall environmental performance of their operations, onshore power systems (OPS), also known as "cold ironing", offer the possibility to provide vessels with (partial) power from shore. A 100% reduction in direct GHG emissions can be achieved if the OPS is powered entirely by renewable or nuclear electricity (which can sometimes be generated near the port).
- Even though most onshore power systems are connected to the grid, supplying auxiliary power to ships in ports with electricity from the shore puts a heavy strain on the electricity grid. Therefore, **ports located in smaller cities, remote locations, or islands may be less suitable for electrification due to the potential lack of regional power generation capacity and/or unreliability of the power grid**. In addition, because electrification of industry and other electric power demands (e.g., port equipment) are expected to result in large increases in power requirements and peak demand in port areas, regions with less robust grid reliability may require backup generation at the port to keep OPS equipment up and running. Finally, the reduction in CO2 emissions per euro invested depends largely on the carbon intensity of the electricity network.
- For this reason, both **mobile** (which can be installed on mobile barges or onshore) **and stationary hydrogen-based system configurations** (i.e., fuel cells, dual-fuel hydrogen internal combustion engines and mono-fuel hydrogen internal combustion engine), **are also being developed, although not yet widely deployed**. These solutions can provide a more flexible way to deliver auxiliary power to ships and can provide a way for ports to develop hydrogen refueling infrastructure for road and maritime applications.

Cold ironing machinery in the port of Stockholm[2]

Note: (1) Hydrogen Europe, 2021; (2) Cold ironing machinery in the port of Stockholm

R&I challenges and associated recommendations for the use of hydrogen in cold ironing

Description of the R&I challenge: Cold ironing provides electrical power to a vessel while at berth, rather than running the ship's engines or generators. Due to direct electrification being more efficient, onshore power supply (OPS) is an important long-term solution applying to vessels. Solutions need to be developed which can provide OPS to these vessels whilst not at berth or when high-power charging facilities are needed in areas with grid limitations. Stationary fuel cells may be well suited for cold ironing, using hydrogen fuel cells to supply electricity for operating the vessel while at quay. However, the use of hydrogen fuel cells for cold ironing is still in the early stages of development.

Objective: **Demonstration of hydrogen fuel cell for cold ironing at ports.**

- **Target for 2030**: Demonstrate cold ironing at ports
- **Cost target in 2030**: NA
- **Research Timeline**: 2023-2030

Where are we today: Ballard offers FCwave, a modular, 200kW system suitable for cold ironing[1]. In the ELEMENTA H2 project a demonstration barge will be embedded with a high-power hydrogen fuel cell system for cold ironing[2]. A 100-kW stationary fuel cell is used for cold ironing in Green Hysland and Every Wh2ere project as well as a 75-kW stationary fuel cell in the BigHit project.

Technical R&I aspects: The concept and the technology for cold ironing is proven and tested but still at an early stage of maturity – particularly in terms of rollout.

R&I projects should focus on:

> Cost reduction (both CAPEX and OPEX), high power density, and BoP system optimization for fuel cell systems for cold ironing including coupling with other forms of energy storage (e.g., batteries or other peak-shaving technologies).
> Standardization of modular systems for the local generation, storage, and conversion of hydrogen.
> Demonstration of improvements in the robustness and lifetime of the fuel cell in operational conditions.

Cold ironing machinery[3]

Recommendation: For those ports where hydrogen fuel cell OPS have been assessed as the most adequate and cost-competitive option, EU (e.g., CEF) and/or national (e.g., fiscal stimulation[4]) **public financial support should be provided to (partially) cover the high capital investment and operating costs associated with hydrogen fuel cell OPS**, and prevent the deterioration of the economic competitiveness position of these pioneer ports. In parallel, the EU and/or Member States should consider to allocate direct **public funding to pioneers in the EU port areas that are launching investments in R&I projects** aiming at further narrowing the cost gap between hydrogen fuel cell OPS and other OPS technology options.

Sources (1) Marine Modules - Fuel Cell Power Products | Ballard Power; (2) Hydrogen barge for electrification of ships at berth; (3) Freight Waves, 2020 (4) For instance, this incentivization can be done through: 1) Investing in specific flagship demonstration projects to prove the technical and economic feasibility of using hydrogen fuel cell OPS; 2) Providing support to identify and secure access to European and/or national public funding programmes; 3) Requiring the inclusion of specific provisions in terminal concession agreements on purchase and operation of (hydrogen fuel cell) OPS; 4) Providing training support for personnel of terminal operators on the use and maintenance of (hydrogen fuel cell) OPS.

Safety challenges and associated recommendations for the use of hydrogen in cold ironing

Description of the safety challenge: Application of hydrogen or hydrogen carriers as a safer alternative for grid based or natural gas based cold ironing systems

Objective: **Development of a safe hydrogen based cold ironing system**

Where are we today: The EU Directive 2014/94 on the deployment of alternative fuels infrastructure provides some input of a regulatory framework for cold-ironing in ports, although based on natural gas[1]. The IEC/ISO/IEEE 80005-1 outlines the specifications of the electric systems (plug designs, voltages, power ratings) needed for cold ironing based on local grids[2]. Several commercial systems are available on the market. The USA started the development of the concept and feasibility of barge-based hydrogen cold ironing systems a decade ago[3].

Safety projects should focus on:

- Safety distances around the cold ironing facility (more important for land-based systems versus barge-based systems).
- Applicability of ATEX zoning on the barge or onshore.
- Safety issues upon swapping empty tanks while the cold ironing system is in service.
- A protocol for first responders in case of a calamity.

Recommendations:

- See recommendation 1 page 80 (recommendation to the European Union (EU) and Member States)
- The EU should encourage the IEC/ISO to **expand/validate the IEC/ISO/IEEE 80005-1 to include hydrogen-based cold ironing systems**.
- The EU should support the development of testing and certification protocols for **swapping empty fuel tanks while the cold ironing system is in service**.
- The EU should support the development of testing and certification protocols for **first responders** in case of a calamity.

Sources: (1) Vichos et al., 2022; (2) European Clean Hydrogen Alliance, 2023; (3) IRENA, 2021.

Non-technical challenges associated with the **use of hydrogen and hydrogen carriers in cold ironing (onshore power supply)**

Non-technical challenges hindering the efficient, rapid and large-scale **use of hydrogen and hydrogen carriers in cold ironing (onshore power supply):**

1. **Lack of port-specific roadmaps** developed by port authorities in collaboration with terminal operators to precisely define key milestones, conditions and responsibilities (i.e., timing, investment needs, required infrastructure and machineries, etc.) **for the complete decarbonization** of port and terminal operation activities**, including cold ironing activities**, before 2050.
2. **Most of the European port authorities and terminal operators seem to favor grid-connected OPS** (**rather than mobile system configurations)** to replace the current use of fossil fuels in ship's onboard combustion engines. Also, the rapid technological development of on-board chargers and battery systems may discourage port authorities from investing in expensive and long-lasting OPS.
3. **Lack of sufficient certainty on the future availability and security of supply of hydrogen/hydrogen carrier fuel** in ports to incentivize port authorities and/or terminal operators to invest in hydrogen fuel cell OPS.
4. **The fairly low threshold for on-site hydrogen storage** (5,000 kg maximum) **defined in the Seveso Directive applies** and discourages port authorities, terminal operators or other third parties from initiating the use of hydrogen as an energy source in cold ironing activities.
5. **The high capital investment and operational costs** required for hydrogen fuel cell OPS may not be commercially viable for small or remote ports and terminals without external public funding and/or fiscal stimulation[1;2].
6. **Lack of sufficient R&I projects to improve supply efficiency** (availability of hydrogen supply capacities and charging time) and therefore improve the attractiveness of the solution.
7. **Lack of policy support to prevent the deteriorating competitive position** of ports that are leading in the implementation of (hydrogen fuel cell) OPS.
8. **Lack of available space** (potentially impacting handling operations) for plugs, cables, and converter stations **to operate** both fixed (grid-connected) and mobile (i.e., hydrogen fuel cell) **OPS**, especially on short quays.

Note: (1) Ports that want to accommodate OPS require investments in physical infrastructure. Stand-alone mobile configurations require an energy storage system, for example a battery module, the mobile configurations could be in the form of a power barge; (2) In the current state of the art, hydrogen fuel cell OPS appears as to be among the most expensive OPS technology options (see page 98 of NOW GmbH, 2022).

Recommendations for addressing non-technical challenges related to the use of hydrogen and hydrogen carriers in cold ironing (onshore power supply)

Responsible authority(ies)**: Port authorities and other port stakeholders**

1 In line with the regulatory provisions established in the FuelEU Maritime[1] and Alternative Fuels Infrastructure[2] proposals, **port authorities should**, in collaboration with relevant public authorities, ensure that OPS facilities are made available to at least containerships (>5.000 GT) and passenger vessels and **lead the evaluation on determining which OPS configurations** (i.e., grid-connected or mobile) **and fuel option** (direct power, battery, hydrogen or alternative fuels) **is best suited to their port-specifics characteristics**[3]. If **port authorities** can not take on the role of building and/or operating (hydrogen fuel cell) OPS facilities (due to port governance and/or national regulatory framework)[4], they **should actively encourage, stimulate or mandate the responsible stakeholders** (i.e., private quay operators) **to ensure** (hydrogen fuel cell) **OPS is made available in sufficient quantities**[5].

Responsible authority(ies)**: The European Union (EU) and Member States**

1 The EU should **work with** the relevant regulatory and standardization authorities (e.g., **CCNR** and **CESNI)** to **establish harmonized technical and safety standards within the EU to facilitate the introduction of cold ironing in ports based on hydrogen and hydrogen carriers**, in accordance with the EU technical, legal and regulatory framework and involve all stakeholders in the maritime sector.

2 **The EU should consider revising the relevant regulatory provisions in the Seveso Directive** so that the **fairly low threshold for on-site hydrogen storage** (5,000 kg maximum) does not apply to port authorities, terminal operators or other third parties willing to initiate the use of hydrogen as an energy source in cold ironing activities.

Notes: (1) In March 2023, the European Parliament and the Council reached an agreement on the FuelEU Maritime regulation to reduce the carbon footprint of Europe's maritime sector, including GHG reduction targets, a 2% target by 2034 for RFNBO uptake in the sector and a 2x multiplier until 2035 (allowing every ton of e-fuel used to be counted twice towards GHG savings) – for more information, see here; (2) The proposal on the Directive on Deployment of Alternative Fuels Infrastructure (COM(2021) 559 final) requires that, by 2030 (or 2025, only for TEN-T core inland waterway ports), sea and inland ports of the TEN-T core and comprehensive networks offer OPS facilities to seagoing container and passenger ships; (3) The German organization NOW GmbH has commissioned a study to Hanseatic Transport Consultancy and MKO Marine Consulting that lay out the technico-economic characteristics (and associated requirements) of using direct power, battery, hydrogen or alternative fuels mobile shore power applications (see: NOW GmbH, 2022); (4) Shore power could be sourced out partially or completely to a concessionaire who is responsible for operations, maintenance and eventually also construction and financing; (5) A limited number of EU Member States have been provided a temporary permit by the EU to apply a reduced rate of taxation to shore-side electricity for ships. The proposal for a revised Energy Taxation Directive could also make it easier to exempt electricity provided to ships at berth (via hydrogen fuel cell OPS) from taxation.

Use of hydrogen and hydrogen carriers in land-base cargo handling and terminal equipment

Photo: Electreck

Introduction: Decarbonisation of port activities using hydrogen and hydrogen carriers as a fuel for port machineries

Description of the activity: Use of hydrogen or hydrogen carrier as a fuel in land-base cargo handling and terminal equipment, such as straddle carrier, terminal tractors, forklifts, rubber-tired gantry cranes and mobile harbor cranes, when direct electrification is not the most cost-efficient decarbonization pathway[1].

Context and background

- In order to meet carbon emission reduction targets set by European and national policy or legislation, European ports need to improve the overall carbon footprint of their operations and reduce the negative impacts of the port or terminals activities on surrounding residential areas (e.g., noise reduction, air pollutant reduction, etc.).
- **Electrification through retrofitting or replacement of existing diesel port equipment with electric drives is often a cost-effective and energy-efficient measure[2] to reduce emissions of port and cargo handling operations[3].**
- However, most cargo handling and terminal equipment remains hard-to-electrify because of (1) high power requirements, (2) poor operational convenience, and (3) long charging times. Also, ports located in smaller cities, remote locations or islands may be less suited to electrification due to potential lack of regional electricity generation capacity.
- Therefore, **when direct electrification is not the most suitable option, port machineries can have their emissions reduced with the use of alternative energy carriers, such as hydrogen (fuel cells) ammonia or e-fuels (e.g., methanol)**. The use of hydrogen and hydrogen-based fuels for port and terminal equipment are currently a less proven technology with lower technological maturity (compared to electrification)[4].
- In the future, complementary to batteries, low-to-zero carbon fuels such as hydrogen (combined with a fuel cell or engine) could be deployed on a larger scale for heavy-duty equipment and/or equipment that have longer periods of operation.

Hydrogen-powered terminal tractor operational in port of Rotterdam (source: link)

Notes: (1) The use of hydrogen or hydrogen carrier as a fuel to power port authorities' own sea-based equipment, such as tugboats, barges, and support vessels is covered in the section 'Use of hydrogen and hydrogen-based fuels in the maritime sector' (slides 66 to 74); (2) Most types of mobile terminal equipment operate internally with electrical drives, with this power generated onboard by a diesel generator. This type of equipment is very suitable for electrification, with drives being directly or indirectly powered by this onboard electrical power grid; (3) Fully-electric equipment is considered zero-emission at the point of use (accounting for the electricity source, energy should be generated by renewables); (4) The German organization NOW GmbH has commissioned a study to Ramboll that lays out the technico-economic characteristics and maturity levels of using diesel, battery (electricity), hydrogen (in combustion engines or fuel cells) or ammonia/methanol (in combustion engines or fuel cells) in various port equipment and machineries ((see: NOW GmbH, 2022 - only available in German).

R&I challenges and associated recommendations for the use of hydrogen as a fuel for heavy-duty port equipment

Description of the R&I challenge: Concerning port operations, rubber-tired gantry (RTG) cranes, yard trucks and material handling vehicles dominate fuel consumption. The need for a continuous and long-lasting operation as well as the inherently high-power demand require a considerable amount of both energy to be stored on-board and available power. Hydrogen may provide an alternative fuel when direct electrification is not feasible. Hydrogen based solutions are still at a prototype stage and need improvement in robustness, aging and cost reduction through standardization of common fuel cell modules.

Objective: **Improve hydrogen fuel cell applications in port area to decarbonize the port operations**

- **Target for 2030**: Energy efficient prototypes using hydrogen fuel cells to power port equipment
- **Research Timeline**: 2023-2040

Where are we today: : H2Ports project to demonstrate and validate use of hydrogen fuel cells for powering reach stacker and yard tractor[1]. Terberg starts intensive testing of hydrogen terminal tractor in the port of Rotterdam[2]. HYSTER to provide hamburger hafen und logistik ag with hydrogen fuel cell-powered empty container handler and terminal tractor[3]. Gaussin has a commercially available hydrogen-powered yard tractor[4].

Technical R&I aspects: The wide variability of operating conditions and tasks characterizing typical Roll-on/Roll-off (RoRo) duty cycle as well as continuous, long-lasting operation for these vehicles represents a crucial aspect.

R&I projects should focus on:

- Co-design and build-up of the port infrastructure including the necessary safety and operational considerations.
- Conversion including retrofit, solutions of existing vehicles and vessels towards hydrogen.
- Improving the new vehicle BoP design, energy management, and system efficiency whilst decreasing the cost (from a TCO) perspective for vehicles within the port with focus of deployment at scale at high TRL.
- Improvements in tools for monitoring and extending the operational lifetime of fuel cell powered equipment.
- Deploying port equipment equipped with fuel cells technologies and the use of hydrogen as zero-emission fuel.
- Scaling up the power, efficiency and operational performance of current prototypes.

*Hydrogen-powered heavy handling tractor **

Recommendation: The EU and/or Member States should consider to allocate direct **public funding to innovative R&I projects** demonstrating the relevant use **of hydrogen or hydrogen carriers as a fuel in cargo handling and terminal activities**.

Notes: (*) GAUSSIN announces a partnership with Terminal du Grand Ouest (TGO) to test the first hydrogen-powered heavy handling tractor.
Sources: (1) (h2ports.eu); (2) terbergspecialvehicles.com; (3) Hyster; (4) Gaussin - ATM 38T Autonomous Yard Tractor.

Safety challenges and associated recommendations for the use of hydrogen and hydrogen carriers in land-based cargo handling and terminal equipment

Description of the safety challenge: Expanding the safe use of hydrogen with road vehicles to use with heavy duty cargo handling vehicles and other port terminal equipment within a port environment.

Objective: **Development of an international standard on the safe use of storage tanks for hydrogen and hydrogen carriers.**

Where are we today: Global Technical Regulations (GTR) 13[1] from UNECE on fuel cell electric vehicles, including composite tanks for gaseous fuel. EN17124 on hydrogen fuel product specification and quality assurance for fuel cell applications for road vehicles. ISO 14687 specifies the hydrogen fuel quality. Road vehicle tanks for gaseous (hydrogen) fuel (ISO 15869)[2] and liquid (hydrogen) fuel (ISO 13985). Based on the EU directive 2014/94 on alternative fuels infrastructure directive (AFID) standards are being developed (M533 and M581)[3] for hydrogen supply to road vehicles and maritime transport. Regulation EC79/2009 specifies harmonized safety requirements for hydrogen-powered vehicles based on an internal combustion engine or fuel cell. Valencia had first hydrogen powered port tractor in 2022[4].

Safety projects should focus on:

- Mechanical integrity of the fuel tank, with focus on the effects due to crash impact and associated development of guidelines for first aid response.
- Safety risks due to flaring of the hydrogen from the fuel tank / formation of a flammable cloud in combination with delayed ignition in a port environment.
- Safety risks posed by a pool fire due to a spill of liquid hydrogen.
- Thermal effects on durability, permeability and mechanical integrity of storage tanks.
- Leakage mechanisms of valves and other devices between the storage tank and fuel cell / combustion engine.

Recommendations:

- See recommendation 1 page 86 (recommendation to the European Union (EU) and Member States)
- The EU should encourage the ISO to **develop (international) standards for vehicle on-board hydrogen storage** (GH2, LH2, ammonia, LOHC) **and the safe integration of on-board storage and hydrogen propulsion systems** – link with ISO 19886; focus on heavy duty vehicles.
- The EU should support the development of testing and certification protocols for **storage tanks**.

Sources: (1) UNECE, 2013; (2) ISO, 2009 ; (3) European Clean Hydrogen Partnershio, 2023; (4) ValenciaPort, 2023

Non-technical challenges associated with the **use of hydrogen (and derivatives) in cargo handling and terminal equipment**

Non-technical challenges hindering the efficient, rapid and large-scale **use of hydrogen and hydrogen carrier as a fuel for port machineries:**

1. **Lack of port-specific roadmaps** developed by port authorities in collaboration with terminal operators to precisely define key milestones, conditions and responsibilities (i.e., timing, investment needs, required infrastructure and machineries, etc.) **for the complete decarbonization of port operation activities** (including cargo handling and terminal equipment) before 2050.
2. **Most of the European port authorities and terminal operators seem to favor direct electrification of land-base cargo handling and terminal equipment (rather than the use of hydrogen fuel)** to replace the current use of fossil fuels in view of decarbonizing port's own activities.
3. **The fairly low threshold for on-site hydrogen storage** (5,000 kg maximum) **defined in the Seveso Directive applies** and discourages port authorities, terminal operators or other third parties from initiating the use of hydrogen as an energy source in port equipment.
4. **Lack of sufficient R&I projects to demonstrate the use of hydrogen or hydrogen carriers as a fuel in cargo handling and terminal activities**, resulting in continued very high acquisition costs of hydrogen-powered cargo handling and terminal machineries compared to traditional diesel engines.
5. **The very high capital investment** required for hydrogen or hydrogen carrier-powered port equipment may **not be commercially viable for small or remote ports and terminals without external funding**.
6. **The use of hydrogen and hydrogen carrier as a fuel for port machineries comes with new and additional challenges on hydrogen and hydrogen carrier fuel supply capacities and space required for charging infrastructure**.

Recommendations for addressing non-technical challenges related to the use of hydrogen (and derivatives) in cargo handling and terminal equipment

Responsible authority(ies): **Port authorities and other port stakeholders**

1. **Port authorities**, which are most often landlord ports, should **actively contribute to encouraging**, **stimulating**, or **compelling** (depending on port governance and regulatory powers) **private terminal operators to decarbonize land-base cargo handling and other terminal equipment** (technological neutral approach).
2. In line with the strategic orientations defined by their respective port authorities, **terminal operators and other port service providers should plan to invest in cargo handling assets and other port equipment powered by alternative fuels** (e.g., battery, hydrogen, ammonia, methanol)[1].

Responsible authority(ies): **The European Union (EU) and Member States**

1. **The EU should work with** the relevant standardization authorities (i.e., **CEN, CENELEC**) **to develop prescriptive harmonized EU-wide regulations, including clear guidelines to Member States on administrative practices and permitting procedures**, **as well as technical, operational and safety standards** for the **construction** and **operation** of **cargo handling** and **other terminal equipment** powered by hydrogen/hydrogen-based fuels.
2. **The EU should consider revising the relevant regulatory provisions in the Seveso Directive** so that the **fairly low threshold for on-site hydrogen storage** (5,000 kg maximum) does not apply to port authorities, terminal operators or other third parties willing to initiate the use of hydrogen as an energy source in port equipment.

Note: (1) For instance, this incentivization can be done through: 1) Investing in specific flagship demonstration projects to prove the technical and economic feasibility of using cargo handling and other terminal equipment powered by hydrogen or hydrogen-based fuels; 2) Providing support to identify and secure access to European and/or national public funding programmes; 3) Requiring the inclusion of provisions in terminal concession agreements to decarbonize port equipment in a medium-term lifespan (e.g., by 2030); 4) Providing training support for personnel of terminal operators on the use and maintenance of new hydrogen or hydrogen carriers-powered equipment; (2) The German organization NOW GmbH has commissioned a study to Ramboll that lay out the technico-economic characteristics and maturity levels of using diesel, battery (electricity), hydrogen (in combustion engines or fuel cells) or ammonia/methanol (in combustion engines or fuel cells) in various port equipment and machineries (see: NOW GmbH, 2022)

Hydrogen and hydrogen carriers-related activities and infrastructure **in the vicinity of ports**

Renewable hydrogen production in ports areas

Photo: Tractabel

Introduction: Port authorities can contribute to the expansion of electrolysis capacity and subsequent renewable hydrogen production in the port area

Description of the activity: Production of green hydrogen from water electrolysis (alkaline, PEM, Solid Oxide[1]) and renewable-based electricity (offshore wind, onshore wind and solar PV) in (large-scale) electrolysers facilities located in the vicinity of ports (either onshore or offshore next to wind farms).

Context and background

- With the continued speedy development of power generation from wind[2] (onshore and offshore) and solar photovoltaic energy in port environments, **the potential for renewable hydrogen production using these locally produced RES may offer interesting opportunities for many European port areas**.
- In this context, in addition to implementing RES production in the port ecosystem (e.g., offshore wind farms located near seaports[3]), **port areas can also provide a suitable location for hydrogen production through electrolysis**. Whether in the form of hydrogen or other chemically processed hydrogen fuels (e.g., ammonia, methanol, e-fuels), which could also be produced in the port, locally produced hydrogen could be consumed in nearby industrial and transportation activities (e.g., marine vessels), or by end-users in the hinterland through transportation from the port (for more information, see slides 120 to 126).
- **Depending on many geoclimatic, spatial, and techno-socio-economic factors, there are a variety of ways in which port authorities could contribute to the expansion of electrolysis capacity** and subsequent hydrogen production in the port area, including (not mutually exclusive):
    - Stimulating the development of electrolysis facilities by **building and operating electrolysis facilities** themselves.
    - **Acting as a landlord and outsourcing the construction** of electrolysis facilities to an experienced operator, who would also be responsible for day-to-day operation and maintenance.
    - **Serving as a project facilitator**, especially by coordinating multiple port-related stakeholders or external parties (e.g., the electrolyzer owner, hydrogen end-users, project developer, contractor, operator, and suppliers of technology components and equipment).

Project Holland Hydrogen I, a 200MW Electrolyser planned to be constructed in the Port of Rotterdam[4]

Notes: (1) The three main electrolysis technologies are alkaline (mature and commercial technology), PEM (Proton Exchange Membrane, more suitable for flexible operation and hydrogen production at higher pressures, less widely deployed), and SOEC (Solid Oxide Electrolysis Cell, not yet on the market, operates at high temperatures, could be used in reverse mode as a fuel cell); (2) Whether onshore or offshore, wind turbines are cost-effective at a minimum scale of about 2 to 3 MW, which leads to significant spatial requirements, as well as to safety risks and neighborhood discomfort; (3) Ports located near other offshore generated energy sources (e.g., floating solar) could also potentially benefit from hydrogen production; (4) Holland Hydrogen I

R&I challenges and associated recommendations for the production of renewable hydrogen in the vicinity of ports

Description of the R&I challenge: Hydrogen may be produced offshore by achieving an association between wind turbines and electrolysers by various approaches. To operate in this environment there is a need for compact electrolysis systems that can withstand harsh offshore environments and have minimal maintenance requirements whilst still meeting cost and performance targets that will allow production of low-cost hydrogen.

Objective: **Demonstrate offshore hydrogen (> 5MW) production and optimize the electrolyser performance for scale up**

- **Target for 2030**: electricity consumption: 48 kWh/kg (AEL, PEMEL); hot idle ramp time: 10 sec (AEL), 1 sec (PEMEL); cold idle ramp time: 300 sec (AEL), 10 sec (PEMEL); Degradation: 0,1 %/1000h (AEL), 0,12 %/1000h (PEMEL)[2]
- **Research Timeline**: 2023-2030

Where are we today: PosHydon operates a pilot production plant at Neptune Energy Q13a-A platform, 13km off the coast of Scheveningen[1]. Lhyfe operates a 440 kg/d offshore production facility powered by a floating wind turbine off the coast of Le Croisic[3]. The OYSTER project will lead to the development and demonstration of a marinized electrolyser designed for integration with offshore wind turbines*.

Technical R&I aspects: Cost effective offshore hydrogen production requires a compact electrolyser with high efficiency. Especially since offshore production is limited in the availability of floor space (space and weight) on the platform. The offshore environment introduces additional challenges on corrosion management, seawater desalinization, plant operation and maintenance.

R&I projects should focus on:
- Deployment of a system that is designed to be remotely controlled, monitored and autonomously operated to minimize operational costs.
- Determination of the long-term performance of the offshore electrolyser in terms of efficiency, performance degradation, integration capabilities, system balancing, corrosion management, operational and maintenance costs.
- Develop control strategies to optimize the plant performances to improve availability, efficiency and production costs.
- Re-using existing offshore infrastructure to decrease cost of installed production.

Offshore hydrogen production facility[3]

Recommendation: The EU and/or Member States **should consider to allocate direct public** funding to pioneers in the EU port areas that are launching investments in R&I aiming at demonstrating **large-scale offshore electrolyzer technologies (> 100 MW)** constructed and operated in a port environment.

Notes: (*) The findings from OYSTER project will inform studies and design exercises for full-scale systems that will include innovations to reduce costs while improving efficiency OYSTER (europa.eu).

Sources: (1) Poshydon | Green Hydrogen Energy; (2) Strategic Research and Innovation Agenda (page 30); (3) Offshore renewable hydrogen (lhyfe.com).

Safety challenges and associated recommendations for the production of renewable hydrogen in the vicinity of ports

Description of the safety challenge: Development of an inherently safe design of large-scale renewable hydrogen production in a port setting, considering the intermittent production behaviour due to the corresponding availability of renewable energy.

Objective: **Development of safety regulations, codes, standards and protocols for large-scale inherently safe production of hydrogen**

Where are we today: Several ISO standards are in place for auxiliary equipment associated with hydrogen production, like separation, purification and compression[1]. ISO 14687 Hydrogen fuel quality, quality control and measurement methodologies. EN 17928 Gas infrastructure and gas grid connection devices, assemblies, as well as materials involved. ISO 22734: Industrial hydrogen generators based on water electrolysis. Several large-scale production facilities are on the drawing board/under construction throughout the EU (for instance Rotterdam - NL, Immingham – UK, Antwerp – BE).

Safety projects should focus on:

- The effect of impurities on the ignition sensitivity of hydrogen/oxygen – hydrogen/air mixtures.
- The hazardous effect of a puncture (worst case rupture) in the membrane separating the oxygen and hydrogen inside the electrolyzer stack.
- Mitigating measures to avoid a potential deflagration inside the electrolyzer stack transitioning into a destructive detonation phenomenon.
- Mitigation measures to avoid the formation of a flammable hydrogen/air mixture as a result of loss of containment inside the facility housing the electrolyzer.
- Considering that large-scale hydrogen facilities will likely be based on the stacking of many modules, the potential interaction between modules as well as failure rates of the elements need to be assessed, potentially leading to domino effects on the production site.
- The intermittent availability of renewable electricity leads to frequent starts and stops, as well as changes in load. This may have an impact on hydrogen cross over (via the membrane) and other safety issues.

Recommendations:

- **The EU is advised to work with** the relevant standardization authorities (e.g., **CEN** and **CENELEC**) to
  - **integrate hydrogen gas quality standards** as well as control strategies considering the intermittent availability of renewable energies;
  - **establish mitigation strategies to avoid the formation of flammable mixtures in-equipment and in-buildings**;
  - **develop measurement methods and test procedures for electrolyser performance**, ranging from single cells to large-scale modular stacks and systems testing protocols.
- The EU should support the development of testing and certification protocols **for** 1) **the performance, failure rates and durability of membranes** and 2) **the detection of in-building flammable atmospheres in facilities housing electrolyzer stacks**.

Sources: (1) European Clean Hydorgen Partnership, 2023

Non-technical challenges associated with the production of renewable hydrogen in the vicinity of ports

Non-technical challenges hindering the efficient, rapid and large-scale **development of green hydrogen production in the vicinity of ports:**

1. **Lack of availability of low-cost RES**, whether due to lack of offshore wind capacity potential in many European coastal regions (i.e., the Mediterranean Sea) or lack of offshore wind installed capacities in regions with high offshore wind capacity potential (e.g., as a result of the lack of social acceptance for the development of renewable energy generation assets in many European port areas and/or the regulatory complexity of the permitting procedure for RES projects[1]).
2. **Lack of available land** (including safety perimeters as a constraint) **near the coastline in port areas** for the installation of large near-shore electrolysers and related equipment (e.g., transformers, rectifiers, water supply, cooling water towers, separators, dryers and compressors).
3. **Lack of available freshwater supply for electrolysers in water-stressed areas** (increasingly frequent with droughts affecting freshwater reservoirs).
4. **Lack of sufficient qualified personnel** (research, engineering, project execution) in port areas for the construction and operation of electrolysers.
5. **Lack of certainty about the willingness of potential end-users to purchase the hydrogen produced**.
6. **Lack of local electrical grid capacity** to cope with the additional production of electricity supplied to electrolysers facilities.
7. **High regulatory complexity of the permitting procedure** for the development of electrolysers facilities.
8. **Lack of/ high regulatory complexity of national procedure for establishing a direct cable connection between an offshore wind farm and an electrolyser located on or near the coastline**, and lack of clarity on which entity ought to be responsible for the development and operation of such cables.
9. **Lack of targeted European and national funding** to support the development of renewable hydrogen production projects near ports, resulting in continued high capital investment requirements for private operators wishing to develop electrolyzer capacities.

Notes: (1) In many European ports, difficulties in obtaining permits for RES projects are linked to local policies and priorities on nature conservation.

Recommendations for addressing non-technical challenges related to the production of renewable hydrogen in the vicinity of ports (1/2)

Responsible authority(ies)**: Port authorities and other port stakeholders (1/2)**

1

Although renewable hydrogen production may not be technically or economically feasible in the vicinity of inland ports and seaports located in areas without significant potential for renewable electricity generation capacity, **port authorities should, in collaboration with local electricity grid operators**[1]**, systematically assess the economic case of renewable hydrogen production activities in their annual investment planning**.

2

Should the case for green hydrogen production in the port area is deemed positive, **port authorities should actively contribute to facilitating or actively participating** (e.g., as a project owner or landlord) **in business consortia to stimulate the development of renewable hydrogen production**. Port authorities could facilitate and coordinate the development of green hydrogen projects involving multiple port-related stakeholders or external parties by:

- **Providing funding support** to initial investment for hydrogen production through electrolysis.
- **Providing support to identify and secure access to European and/or national public funding programmes**.
- **Ensuring connection of electrolyzer facilities to local electricity grids and district heating networks** (notably to allow residual heat from electrolysers to be used elsewhere in the port area).
- **Ensuring the accommodation of power cables and/or pipelines** coming in from offshore/onshore RES or hydrogen production installations.
- **Ensuring the availability of basic operational utilities and services** (e.g., road access, maintenance, piping, cabling, etc.) necessary for the safe and efficient construction and operation of electrolyzer facilities.
- **Connecting project developers and electrolyzer operators with green hydrogen end-users**.
- **Coordinating the development of connections to transport** (water/road/rail/pipelines) **the locally produced hydrogen** from the port area to the local industrial facilities and/or to the hinterland.
- **Encouraging terminal operators to store parts/equipment of electrolyzer facilities**.
- **Encouraging existing hydrogen-consuming and energy intensive industries to move towards a closer vicinity of the port**.

3

For ports with nearby offshore oil and gas platforms, port authorities should **explore the technico-economic potential of repurposing these platforms for hydrogen production** from wind power after decommission due to the end of oil and gas economic life in the coming decades (especially in the North Sea).

Notes: (1) In some port areas (especially in locations with significant offshore wind generation), the local power grid may experience congestion, resulting in renewable-based electricity curtailment). In such cases, the development of electrolysis facilities would be of particular value in order to accommodate excess electricity generation, resulting in a more positive economic outcome for green hydrogen production.

Recommendations for addressing non-technical challenges related to the production of renewable hydrogen in the vicinity of ports (2/2)

Responsible authority(ies)**: Port authorities and other port stakeholders (2/2)**

4

While it can be typically expected that future onshore electrolyzer facilities will be directly connected by power cables to offshore wind farms, port authorities should also **explore the technico-economic potential of building dedicated offshore electrolyzer facilities nearby offshore wind farms and then transporting the locally produced hydrogen to the shore via submarines pipelines** for distribution to end-users, transport to the hinterland or storage.

Responsible authority(ies)**: The European Union (EU) and Member States**

1

In a view of de-risking investments in required production infrastructure, **Member States should design the appropriate policy and regulatory framework** enabling efficient, rapid and large-scale uptake of renewable **hydrogen production activities in port areas**. This includes:

1. **The establishment of national environmental, planning and safety legislation** (e.g., authorization procedure, safety standards, spatial integration requirements) for the design and operation of electrolysis installations in port areas.
2. **The classification of power cables connecting onshore or offshore renewable electricity generation facilities and electrolysers in national electricity legal regimes** and the **adoption of provisions on the ownership and operation of such cables**.
3. **Addressing the growing concern over the lack of availability of freshwater supplies** (due to increasingly frequent and intense droughts affecting freshwater reservoirs) needed for green hydrogen production. Alternative water sources, such as sea water or treated wastewater may need to be leveraged in the coming years and decades in response to freshwater scarcity.

Surface hydrogen and derivatives storage solutions

Photo: NASA

Introduction: Additional capacity for hydrogen and hydrogen carrier storage in tanks will be required to be constructed in port areas (1/2)

Description of the activity: Above-ground storage of hydrogen and hydrogen carriers in stationary or mobile tanks at import terminals, either in compressed (compressed hydrogen) or liquid (LH_2, ammonia, LOHCs, methanol) form, for short- to medium-term (hours or days/months) storage prior to transport to locations with high demand for green hydrogen and low local production possibilities[1].

Context and background (1/2):

- Local production and import (via intercontinental ships) of green hydrogen will have an impact on storage facilities in port areas[2]. In the framework of the REPowerEU plan (about 4 Mt of hydrogen imported into the EU per year by 2030 via ships) and given that space currently used by oil and LNG storage tanks are not expected to be freed up in the coming years/decades, **additional capacity for hydrogen and hydrogen carriers in tanks will be required to be constructed in port areas for short- to medium-term** (hours or days/months) **storage** prior to transport to locations with high demand for green hydrogen and low local production possibilities.
- **Above-ground storage of hydrogen and hydrogen carriers in tanks can be achieved in a variety of ways**. Although hydrogen can technically be stored in pressurized gas form (GH2), the energy density per volume is low and transporting pressurized gas requires solid steel containers, which is not done at scale today. Therefore, hydrogen storage is generally in liquid form (higher energy density per volume), either as LH2[3] or via liquid hydrogen carriers (ammonia, methanol or LOHC)[4]. It must however be considered that LH2 and liquid hydrogen carriers have less energy density than fossil fuels (e.g., for the same amount of energy stored, relatively to diesel LH2 needs 4 times the volume and ammonia 3 times[5]). On top of the lower energy densities compared to fossil fuels, due to the safety characteristics of the hydrogen and hydrogen carriers (e.g., ammonia is highly toxic, and hydrogen is flammable), **significant space is required to adhere to the safety distance obligation**[6].

Liquid hydrogen Tank at NASA Kennedy Space Center (source: link)

Notes: (1) Given that hydrogen transport via pipeline is out of scope of this study, the so-called line packing hydrogen storage option, which refers to the volume of gas that can be "stored" in a gas pipeline, is not assessed. All in all, line packing has the potential to provide only a marginal share of storage needs, with the bulk being satisfied by underground storage[1]. Small-scale above-ground storage could be a particularly competitive activity, given 1) low barriers to entry; 2) lower relevance for system planning; and 3) that it will be required to some extent for end-users and rail / ship / transport[1]; (2) On the one hand, the total capacity of offshore wind energy generation is expected to increase significantly in the coming years and is likely to exceed the grid capacity and local demand. Hydrogen can then be produced with this 'excess' energy and stored as buffer for local use in time of low wind or for onwards global transport to locations with high energy demand but low local production possibility. On the other hand, the unfolding of the REPowerEU plan is expected to lead to significant amount of hydrogen (around 4Mt per year by 2030) being imported to EU ports via ships; (3) Today, large-scale liquid hydrogen storage technology is relatively similar to that of the 1960s, with the largest facility at NASA's Kennedy Space Center (Florida, United States). It is a double-walled vacuum cryogenic insulated sphere, used for space applications, with a capacity of 3,200 m3 (230 tonnes). In addition, construction of a new spherical tank by CB&I, with a capacity of 4 700 m3, is nearing completion also at NASA (See Cryogenic Society of America, 2022); (4) Ammonia requires refrigerated insulated tanks and methanol and LOHC are liquid under ambient conditions; (5) LOHCs have even larger storage requirements compared to ammonia and methanol. It needs large amount of storage, due to the volume of the carrier material; (6) For instance, large scale ammonia storage and handling requires double the safety distances currently required and implemented for LNG. **Sources**: EnTEC, 2022; Institute of Sustainable Process Technology, 2019; Royal HaskoningDHV, 2022

Introduction: Additional capacity for hydrogen and hydrogen carrier storage in tanks will be required to be constructed in port areas (1/2)

Context and background (2/2):

- In the decades to come, hydrogen and hydrogen carriers can be expected to be **stored in large volume tanks of the same order of magnitude as current LNG tanks** (tens to hundreds of thousands of cubic meters)[1]. Therefore, as with current LNG imports, **large European seaports** located in proximity to deep water **are best positioned to become hydrogen and hydrogen carrier storage hubs**[2]. Smaller sea and inland ports would likely be best located to accommodate smaller volumes of liquid bulk storage for later transportation (e.g., via inland waterways) to remote users (not connected to hinterland pipelines) or for use as marine fuel for local vessels.
- In this context, port authorities could play a key role in **engaging with the various stakeholders to facilitate the development of hydrogen and hydrogen carrier storage facilities**. In particular, port authorities could contribute to the expansion of hydrogen and hydrogen carrier storage capacity in the port area by taking any of the following actions (not exclusive of each other):
  - By acting as the project manager and storage facility owner, and ensuring that cargo handling and industrial activities conducted nearby the storage area can be still conducted in a safe and efficient manner.
  - By acting as a landlord and outsourcing the construction and day-to-day operation and maintenance of storage facilities to experienced energy supply companies.
  - By serving as a project facilitator and coordinator and ensuring the implementation and enforcement of the relevant security measures for these liquid fuels by the various stakeholders.

Small-scale hydrogen storage tanks (source: link)

While the storage considerations for hydrogen and hydrogen carriers in above-ground tanks are already incorporated into the broader discussions in the section on '*Hydrogen and hydrogen carrier import terminals*' (slides 47 to 55), this section focuses solely on above-ground storage solutions for hydrogen and derivatives in all kind of port areas (import and non-import ports).

Note: (1) Only a small number of liquid hydrogen tanks exist today, and their capacity is substantially lower than for LNG. Existing tanks are usually of smaller capacity (e.g., approx. 600 m3 They have not been scaled up yet, as there was no need for larger hydrogen tanks. Capacity of LNG tanks vary from 50,000 m3 to 250,000 m^3. In total, LNG tank capacity in the EU is 8.5 - 9.1 Mm^3, translating to up to 173 (bcm(N)/year) regasification capacity; (2) In December 2021, Shell and the consortium partners—including McDermott's CB&I Storage Solutions, NASA's Kennedy Space Center, GenH2 and the University of Houston—have been selected by the U.S. Department of Energy's (DOE) Hydrogen and Fuel Cell Technologies Office to demonstrate that a large-scale LH2 tank, with a capacity ranging from 20,000 to 100,000 cubic meters, is both feasible and cost competitive at import and export terminals. The project is 50% co-financed by a USD 6 million grant from the US DOE under the H2@Scale initiative (See McDermott International, Ltd, 2021).

Sources: EnTEC, 2022; Institute of Sustainable Process Technology, 2019; Royal HaskoningDHV, 2022

R&I challenges and associated recommendations for the development of liquid hydrogen above-ground storage infrastructure

Description of the R&I challenge: Above ground hydrogen of liquefied hydrogen requires high performance materials to withstand very low temperatures and limit heat ingress.

Objective: **Installation and operation of large-scale unit for storage of LH2 at ports**

- **Target for 2030**: Individual storage size: > 50.000 m3*; LH2 boil-off rate: < 0,1% day**
- **Cost target in 2030**: Capital cost < 600 euros/kg of LH2[1]
- **Research Timeline**: 2022-2030

Where are we today: NASA operates an LH₂ storage tank with a size of 3,800 m3 and storing around 270 tons of LH₂. Kawasaki Heavy Industries (KHI) Ltd. designed a pilot of stationary, land-based LH2 storage tanks based on current space industry storage tanks*. CB&I has completed the conceptual design of a 40.000 m3 LH2 sphere[5].

Technical R&I aspects: LH_2 storage presents several new challenges that greatly impact scalability, most namely the insulation of the tank to withstand heat ingress which increase the boil-off rate. The insulation concepts developed so far are rather complex and costly. At present, nearly one year is spent on site erection for a 150 tonnes LH_2 storage. For the import of LH_2 at energy system scale, in the order of GW hydrogen energy flux, larger scale LH_2 storage tank concepts need to be developed.

R&I projects should focus on:

- Development of advanced materials to reduce lifecycle cost, producing lighter solutions.
- Development of novel insulation concepts, reducing manufacturing cost whilst maintaining low boil-off rates.
- Development of alternative storage methods using solid nanostructured absorbers (microporous materials, metal-organic framework materials).
- Detailed design, construction, and testing of a scaled-up prototype of at least 50.000 m3 LH2 capacity*.

LH2 storage at NASA (source: NASA)

Recommendation: : The EU (e.g., through CEF-Energy, IPCEI) **and/or Member States** (e.g., though State aid for climate, environmental protection and energy) **should consider to allocate direct public funding to pioneers in the EU port areas** that are launching investments in market-ready projects aiming at decreasing the cost of large-scale LH_2 storage tanks in a port environment.

Notes: (*) These are double-shell spherical tanks that have perlite vacuum thermal insulation and a capacity of about 2,500–3,000 m3; KHI believes they could scale up to 50,000 m3 (Kamiya, Nishimura, & Harada 2015)(**) (boil-off ratio depends on tank size and intended usage pattern).

Sources: (1) Strategic Research and Innovation Agenda (page 158); (2) Ortiz Cebolla et al., 2022; (3) The role of renewable H₂ import & storage to scale up the EU deployment of renewable H₂ - Publications Office of the EU (europa.eu); (4) Innovation Outlook: Renewable Ammonia,2022; (5) CB&I completes conceptual design.

R&I challenges and associated recommendations for the development of compressed hydrogen above-ground storage infrastructure

Description of the R&I challenge: Above ground storage of compressed hydrogen requires high performance materials such as high-performance steels, aluminum or composites to withstand high pressure. As these materials substantially affect the cost and mass at system level, it is critical that lower cost and lighter storage solutions are developed for hydrogen technologies to be adopted widely.

Objective: **Development of advanced materials to reduce cost and mass of compressed hydrogen storage**

- **Cost target in 2030**: Capital cost < 600 euros/kg of compressed H2
- **Research Timeline**: 2022-2030

Technical R&I aspects: Gaseous hydrogen storage tanks are commonly grouped in four categories, Type-I, II, III and IV*. Type-I all metal cylinders are most commonly used. The tensile strength, resistance to hydrogen embrittlement and gas permeability are the main obstacles for stationary storages[1]. Hydrogen gas is usually compressed to pressure values starting from 100 and up to 825 bars[1].

R&I projects should focus on:

> Development of advanced materials to reduce lifecycle cost, producing lighter solutions.

Compressed hydrogen storage bank[2]

Recommendation: : The EU (e.g., through CEF-Energy, IPCEI) **and/or Member States** (e.g., though State aid for climate, environmental protection and energy) **should consider to allocate direct public funding to pioneers in the EU port areas** that are launching investments in market-ready projects aiming at developing **advanced materials to reduce cost and mass** of large-scale GH2 storage tanks in a port environment.

Notes: (*) Type-I: All-metal cylinder; Type-II: load-bearing metal liner hoop wrapped with resin-impregnated continous filament; Type-III: non-load bearing metal liner hoop wrapped with resin-impregnated continous filament; Type-IV: non-load bearing, non-metal liner hoop wrapped with resin-impregnated continous filament.

Sources: (1) Elberry, A.M. et al - Large-scale compressed hydrogen storage; (2) Nel Hydrogen - Hydrogen Fueling Storage.

R&I challenges and associated recommendations for the development of hydrogen derivatives above-ground storage infrastructure*

Description of the R&I challenge: Ammonia has been handled in large quantities for many decades, and there is a high maturity of storage technologies[1]. Most LOHCs can be stored in conventional liquid bulk terminals as their physicochemical properties are similar to conventional petrochemical products.

Where are we today: Large ammonia storage facilities are typically located at ports near ammonia production facilities, with up to 150 kt of ammonia storage capacity divided over multiple tanks[1]. LOHC are mostly oil derivatives and could build upon existing facilities with no boiloff losses and a liquid state at ambient conditions.

Technical R&I aspects: There are three main types of liquid ammonia storage methods: pressurized, semi-refrigerated and refrigerated. The required storage capacity is the main factor determining the type of storage methods. Pressurised storage is usually preferred for low volumes while refrigerated storage is preferred as the scale increases since the tanks use less steel and are therefore more cost-effective. At scale, ammonia is liquefied by refrigeration at -33˚C and atmospheric pressure. Boil-off due to heat ingress is the main concern[1]. The largest ammonia tanks can store up to 50 kt of ammonia[1,2]. Most LOHCs can be handled like a fossil liquid due to its characteristics as a flame retardant and non-explosive carrier with a high volumetric energy density. Therefore, LOHC can be stored in existing tanks, at ambient pressure and temperature.

R&I projects should focus on: No R&I challenges identified.

Ammonia storage TK3201 at VOPAK's Banyan terminal in Singapore[3].

Recommendation: No technological barriers identified.

Notes: (*) This analysis focuses on ammonia and LOHC as the main hydrogen carriers, other carbon-based fuels and solid carriers are relevant but outside the scope of this analysis;

Sources: (1) Innovation Outlook: Renewable Ammonia,2022; (2) McDermott - QAFCO Ammonia Storage Tanks; (3) Vopak explores new ammonia infrastructure in Singapore.

Safety challenges and associated recommendations for the development of above-ground hydrogen and hydrogen derivatives storage infrastructure

Description of the safety challenge: The energy transition requires the storage of vast amounts of flammable and/or toxic hydrogen carriers that have a minimum impact on external safety and a trusted by the population. For this new and safe storage facilities need to be erected that require innovations in the materials used and protocols applied.

Objective: **Safe large-scale storage of hydrogen and hydrogen carriers in above ground storage facilities.**

Where are we today: Using EN 1918-5 (underground gas storage) for functional recommendations for surface facilities. The ISO 15916 [1] focuses on the basic considerations of the safety of hydrogen systems, focused on hydrogen itself. The EN 13445-1 and EN 13480 provide design and stress calculation considerations of pressure vessels containing pure hydrogen or natural gas blends. LOHCs are higher hydrocarbons, are diesel like and the lessons learned can be directly applied. Methanol and ammonia are known chemical intermediates and the lessons learned can be implemented.

Safety projects should focus on:

- External safety considerations for large-scale liquid hydrogen storage; position of venting lines during (especially) filling the storage facility.
- Permeability and leakage mechanisms of gaseous hydrogen and ammonia leading to (hazardous) external safety issues – safety distances.
- Safety considerations in the building norms for hydrogen storage facilities in gaseous and liquid form; with the latter attention needs to be given to safety mitigation measures in case of a loss in cooling or in case of a pool fire due to a significant spill/leak.

Recommendations:

- The EU should **encourage the ISO to**
  - **include LOHC in ISO 15916** (consideration for the safety of hydrogen systems);
  - **adapt the current standards on LNG to liquified hydrogen and compressed/refrigerated ammonia;**
  - **develop guidelines for maritime bulk storage of hydrogen carriers covering both existing and new terminals**. This includes conversion services (liquefaction, (de)hydrogenation, purification);
  - **develop a technical standard for tank volume, tank typology, tank farm lay-out and tank pressure** (when applicable) in relation to external safety/safety distances, considering the SEVESO III guideline.

Sources: (1) European Clean Hydrogen Alliance, 2023

Non-technical challenges associated with the development of above-ground hydrogen and hydrogen derivatives storage infrastructure

Non-technical challenges hindering the efficient, rapid and large-scale **development of above-ground hydrogen and derivatives storage infrastructure:**

1. **Lack of certainty about the future supply of hydrogen and hydrogen carrier in ports** on a scale that will require storage facilities.
2. **Lack of available land** (including safety perimeters as a constraint) **near the coastline in port areas** for the construction of new large (tens to hundreds of thousands of cubic meters) volume hydrogen or hydrogen carrier storage tanks.
3. **Strong social and public resistance for the construction and operation of ammonia storage facilities**, especially in ports located near densely populated areas, due to toxicity and smell of the substance.
4. **Lack of sufficient European and national funding** to support the development of hydrogen or hydrogen carrier storage tanks near ports, resulting in continued high capital investment requirements for private operators wishing to develop storage capacities.
5. **Lack of sufficient qualified personnel** (research, engineering, project execution) for both the repurposing of LNG tanks or the construction of new LH2 thanks.

Notes: (1) **Storage of CH_2 in tanks:** Currently already done at the small scale in the EU, CH_2 tanks are usually either placed on hydrogen tube trailers for transportation purposes or in racks for stationary storage and usage (i.e., at industrial sites or at hydrogen filling stations). Scaling up CH_2 tank size or increasing the pressure beyond 200 bar is economically challenging due to need for special materials and high operating costs; (2) **Storage of LH_2 in tanks**: Even though LH_2 storage is already being done by space agencies for rocket fuel around the globe (current aggregate global hydrogen liquefaction capacity is reported to be around 355t per day), further development of technology is required for the LH2 storage market to increase (in particular, further design innovation is needed to increase tank size). In parallell, there is theoretically substantial potential for hydrogen storage in repurposed existing LNG tanks at port terminals, although the ease of converting an existing LNG tank for LH2 is viewed differently in literature (Fraunhofer ISI, 2022); (3) **Storage of ammonia in tanks**: Even though under very strict regulations, storage of ammonia in tanks is a proven technology already widely used in Europe (more than 50 refrigerated ammonia storage tanks in operation) in the fertilizer industry. The largest ammonia tank is located in China and has a capacity of 30,000-80,000 m3 , which is substantially smaller than the typical LNG tank sizes of 200,000 to 250,000 m3. In Rotterdam, a new import terminal handling ammonia volumes of approx. 1,780.000 m3 (1.2 Mt) by 2023 is planned. The conversion of LH2 tanks into ammonia thanks is considered to be feasible, but, nonetheless, a complex technical overhaul. T (Fraunhofer ISI, 2022). (4) **Storage of methanol in tanks**: Currently already done at the large scale in the EU, methanol tanks have the advantages to have no safety-related limitation on where they can be located (even though methanol is a flammable product); (4) **Storage of LOHCs in tanks**: Currently already done at the large scale in the EU, LOHCs tanks have the advantages to have no safety-related limitation on where they can be located and to be fit for using the currently available gasoline transport infrastructure for fuel distribution.

Recommendations for addressing non-technical challenges related to the development of **above-ground hydrogen (derivatives) storage infrastructure** (1/2)

Responsible authority(ies)**: Port authorities and other port stakeholders**

1

Under the leadership of port authorities and in close collaboration with all relevant parties in port areas (terminal operators, alternative fuel storage owners, ship tankers companies, etc.), **each port ecosystem should consider and assess the societal relevance and the techno-economic rationale for the development of hydrogen or hydrogen carrier storage activities in the vicinity of their ports**. **This consideration should be particularly strengthened for large European seaports already involved in oil and gas import and storage activities.** To that end, should the case for hydrogen or hydrogen carrier storage activities in the port area is deemed positive, **port authorities should actively contribute to encouraging** and **stimulating** (either as a project owner, landlord or project facilitator) **in business consortia** that aim at developing hydrogen or hydrogen carrier storage facilities at scale. In particular, port authorities could facilitate and coordinate the development of hydrogen and hydrogen carriers' storage projects involving multiple port-related stakeholders or external parties by:

- **Identifying land areas** in the vicinity of the port that would be suitable for the construction and operation of hydrogen or hydrogen storage facilities.
- **Promoting social and public acceptance** of hydrogen and hydrogen carriers (e.g., ammonia) storage facilities among port stakeholders and local populations.
- **(Co-) investing in specific flagship demonstration projects** to demonstrate the technical and economic feasibility of the safe storage of hydrogen or hydrogen carriers in the vicinity of ports.
- **Ensuring the availability of basic operational utilities and services** (e.g., road access, maintenance, piping, cabling, etc.) necessary for the safe and efficient construction and operation of hydrogen or hydrogen carrier storage facilities.
- **Bringing together relevant public and private stakeholders** (e.g., fuel importers, storage infrastructure owners and fuel transporters (to end-users in the hinterland).
- **Encouraging existing hydrogen-consuming and energy intensive industries to move towards a closer vicinity of the port**.

2

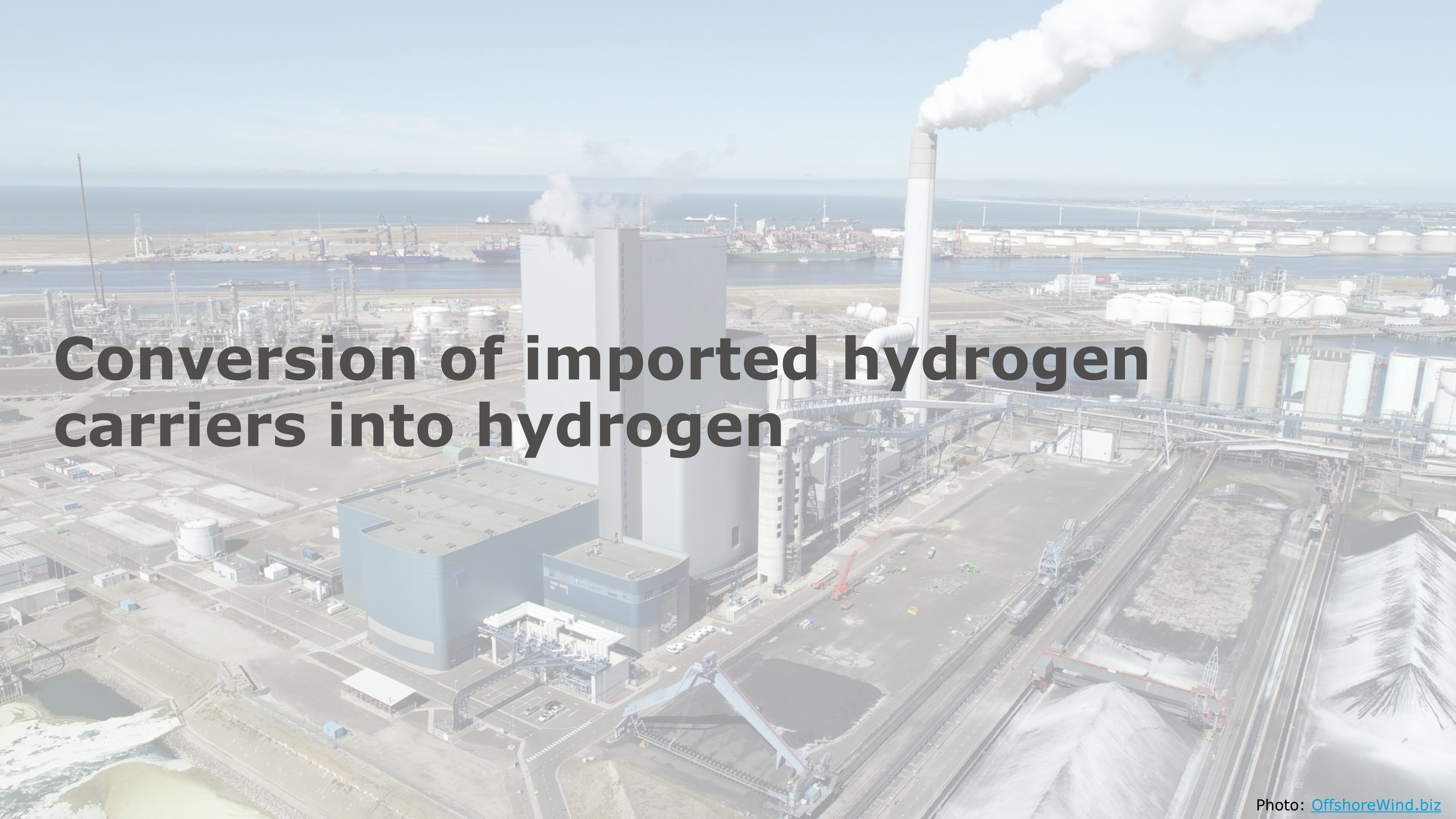
Due to the significant spatial requirements related to safely building and operating above-ground storage of hydrogen and hydrogen carriers in tanks, and the likely development of several forms of imported hydrogen and hydrogen carriers, **ports** willing to engage into hydrogen or hydrogen carrier storage activities **could consider to specialize in the storage of one particular form of hydrogen or hydrogen carriers**.

Recommendations for addressing non-technical challenges related to the development of **above-ground hydrogen (derivatives) storage infrastructure** (2/2)

Responsible authority(ies)**: The European Union (EU) and Member States**

1. In areas where social and public acceptance concerns are likely to interfere with the foreseen increase in hydrogen or hydrogen carriers (e.g., ammonia) storage activities, **strategies and associated actions** (e.g., by involving local communities in project development or launching public information campaign) **should be defined to minimize social and public opposition to the development of storage infrastructure**.

2. For planed LNG storage thanks, given that converting LNG tanks for use with LH2 or ammonia is only seen as feasible if a concept for the conversion has been made in the construction phase of the LNG tanks and has been taken into account in the material selection of the tanks, all **large-scale LNG storage tanks** currently under construction or planed **should be designed considering later conversion to LH2 or hydrogen carriers** (e.g., ammonia).



Conversion of imported hydrogen carriers into hydrogen

Photo: OffshoreWind.biz

Introduction: Conversion facilities may need to be built for the recovery of hydrogen from hydrogen carriers (ammonia, LOHC) at import terminals

Description of the activity: Conversion of imported hydrogen carriers (ammonia or LOHC) into hydrogen (in its gaseous form) through the construction of industrial-scale ammonia cracking and LOHC dehydrogenation facilities in European import terminals.

Context and background:

- When the product demand is GH2, **conversion facilities will need to be built for the recovery of hydrogen from hydrogen carriers** (ammonia, LOHC) **at import terminals**. For ammonia, hydrogen can be recovered using **ammonia crackers** that break down the ammonia into nitrogen and hydrogen. **For LOHC**, hydrogen can be recovered using a **dehydrogenation process**.
  - **Ammonia cracking**: Industrial-scale ammonia crackers in European ammonia import terminals are **not yet commercially available**, mainly due to the lack of maturity of the technology (TRL 3) and the very high energy requirements (around 30% of the energy content of the fuel are needed to provide the heat)[1]. Given that this situation could turn over economic benefits of the ammonia conversion[2], the first pilot projects aiming at demonstrating the technico-economic feasibility of industrial-scale ammonia crackers are being lunch in a few European countries (Germany, the Netherlands, Denmark and the UK)[3].
  - **LOHC dehydrogenation**: Same as for ammonia cracking, **the technological maturity of large-scale LOHC dehydrogenation is low** (TRL 3) and is highly energy-intensive (around 35-40% of the energy content of the hydrogen is needed in the process)[4]. Some first pilot projects aiming at demonstrating the technico-economic feasibility of industrial-scale LOHC dehydrogenation are being lunch in a few European countries (Finland, the Netherlands, Germany) and Asian (Japan, Singapore) countries[5].
- **For the port authorities, the conversion of imported ammonia and LOHC to hydrogen will require large amounts of vacant land as well as increased energy supply needs** (electricity and heat)[6].

Ammonia plant[7]

Notes: (1) Although ammonia cracking is already commercially available and used in metallurgy, it exists only on a very small scale (1-2 tpd), rarely includes hydrogen purification, and is highly energy intensive (due to the high temperatures required, in the range of 600-900°C); (2) It is likely that the first imported green ammonia will be used directly in ammonia end-uses applications. It is only at a later stage when green hydrogen demand will be already high that ammonia import terminals are expected to crack hydrogen out of ammonia; (3) In Germany, three ammonia cracking pilot projects are being launched: the TransHyDE project AmmoRef (see FCHEM), the Green Wilhelmshaven project, in the port of Wilhelmshaven (see Uniper), and the RWE project, in the port of Brunsbüttel (see RWE, 2022). In Denmark, the company Haldor Topsøe is working on the design of a 5-500 tpd ammonia cracking plant (see Haldor Topsoe A/S, 2021). In the Netherlands, Proton Ventures was awarded subsidies from the Rotterdam government for the development of an ammonia cracker (see Proton Ventures, 2022), the companies Air Products and Gunvor have announced a joint development agreement for an ammonia import terminal in Rotterdam by 2026, and the subsequent conversion of ammonia to hydrogen (see Gunvor Group, 2022) and the companies HES International and Vopak are planning on developing in the port of Rotterdam a new ammonia import terminal (ACE Terminal) associated with an ammonia cracking facility (see ACE Terminal); (4) Although some degradation occurs, the carrier molecule can be reused, but it needs to be shipped back to the export terminal, resulting in additional shipping fuel consumption (only slightly higher than for an empty ship); (5) In Finland, the HySTOC project commissioned a LOHC hydrogenation and storage facility to supply hydrogen to a refueling station, where the dehydrogenation unit is located (see HySTOC, 2021). In the Netherlands, the Port of Rotterdam, Koole Terminals, Chiyoda and Mitsubishi signed a MoU to assess the potential of using LOHC technology to import hydrogen to port of Rotterdam (see Mitsubishi Corporation, 2021). In Germany, the AquaVentus project plans to produce hydrogen and to transport it via LOHC to a dehydrogenation plant to be built at the Port of Hamburg (see AquaVentus, 2021); (6) As well as storage space for hydrogen carriers at the conversion sites and compressor stations to compress hydrogen to the pressure required for injection in the pipeline; (7) Ammonia plant. **Sources**: Fraunhofer ISI, 2022; IEA, 2022, Clean Hydrogen JU, 2022

R&I challenges and associated recommendations for the development of ammonia reforming infrastructure

Description of the R&I challenge: Ammonia reforming (cracking) is an endothermic process with current catalysts operating in a temperature range of 600-900 C. Current ammonia reformer technology has been demonstrated at small scale (1-2 tpd) and **requires a demonstration at industrial scale** to reach the desired maturity and de-risk design at large-scale. To improve the overall value chain efficiency of hydrogen transport through ammonia**, the thermal efficiency and conversion has to be improved.**

Objective: **Demonstrate ammonia reforming at industrial scale in ports**

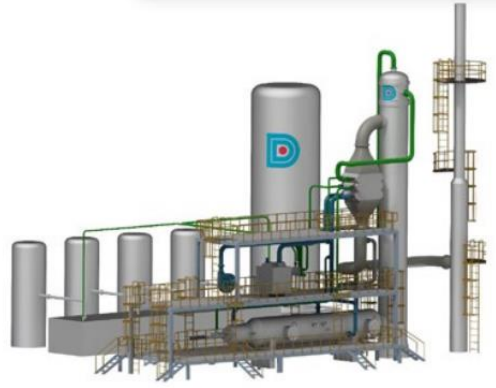
- **Target for 2030**: > 1000 t H2/d
- **Cost target in 2050**: < 2 € /kg H2*
- **Research Timeline**: 2023-2030

Where are we today: Ammonia reformers are commercially offered at industrial scale by several technology providers[2,5,6]. Port of Rotterdam along with other commercial partners is conducting a feasibility study to convert imported ammonia to 1 million tons/year of H_2 (6 million tons of NH_3) using ammonia cracking The AmmoRef project, which received funding in 2021, aims to develop new catalysts and technologies for ammonia reforming[3].

Technical R&I aspects: State of the art ammonia reformers are reaction units principally based on fired or partial oxidation reformers. The thermal energy required is a restricting challenge. Typically, ammonia is used as a fuel. Component thermal losses, power consumed by pumps, emissions, imperfect recovery in conventional purification and use of critical raw materials represent additional challenges.

R&I projects should focus on:

> Technology demonstration at industrial scale (40-80 kt/a) to de-risk ammonia cracking at larger capacities as well as to provide operating hours to establish license agreements.
> Development of catalyst to improve selectivity, conversion, operating temperature and material usage to reduce downstream purification, recycling, specific energy input and costs.
> Development of reactor design to improve thermal efficiency, ammonia slip and capacity.
> Development of burner design to reduce NOx emissions for ammonia fired reformers.
> Upscaling of e-cracker concepts for ammonia reforming.
> Alternative purification technologies to meet downstream standards to prevent tail-gas formation in PSA.



Ammonia-to-Hydrogen Convertor[2]

Recommendation: The **EU** and/or **Member States** should consider **to allocate direct public funding to pioneers in the EU port areas** that are launching investments in R&I projects aiming at **advancing the technological maturity of industrial-scale ammonia cracking** near hydrogen carrier import terminals, and demonstrate their techno-economic feasibility (i.e., cost reduction, improved process efficiency, etc.)

Notes: (*) Total cost attributable to a hydrogen carrier system to supply, on average, 1000 tpd of Hydrogen over a round trip distance of 3000 km, expressed on a per kg hydrogen delivered basis;.

Sources: (1) Clean Hydrogen JU Work Programme 2022; (2) https://duiker.com/; (3) Clariant developing next-gen ammonia cracking catalyst; (3) Port of Rotterdam kicks off study into ammonia cracker - Port Technology International; (4) Strategic Research and Innovation Agenda (page 158); (5) Topsoe H2retake-process; (6) KBR.

R&I challenges and associated recommendations for the development of LOHC dehydrogenation infrastructure

Description of the R&I challenge: LOHC dehydrogenation is an endothermic process with current catalysts operating in a temperature range of 200-400 C. Current LOHC dehydrogenation technology has been demonstrated at small scale (1 kg/h)[1] and **requires a demonstration at semi-industrial scale** to reach the desired maturity and de-risk design at large-scale. To improve the overall value chain efficiency of hydrogen transport through LOHC**, the selectivity, conversion and thermal efficiency of the process has to be improved.**

Objective: **: Demonstration of LOHC dehydrogenation at semi-industrial scale**

- **Target for 2030**: scale: >100 t H2/day; specific energy consumption: < 12 kWh/kg H2
- **Cost target in 2030**: < 2 €/kg*
- **Research Timeline**: 2023-2030

Where are we today: Hydrogenious demonstrated LOHC dehydrogenation to produce fuel cell grade hydrogen at small scale(1 kg/h H2)[2]. Joint venture LOHC logistix is constructing a 1,5 t H2/d dehydrogenation plant in Rotterdam[3]. The H2A project aims to import up to 1 Mtpa H2 to the Port of Amsterdam through LOHC technology[4].

Technical R&I aspects: The thermal energy required for dehydrogenation is a restricting challenge. Moreover, components thermal losses, power consumed by pumps, and loss of hydrogen due to imperfect recovery in conventional separation and purification section represent other important issues to address for the next generation LOHC dehydrogenation plants.

R&I projects should focus on:

- Development of catalyst to improve selectivity, conversion, operating temperature and material usage to reduce byproduct formation, downstream purification, recycling, carrier loss, specific energy input and costs.
- Development of reactor design to improve thermal efficiency and capacity.
- Development of innovative reactors and catalyst for the dehydrogenation of LOHC, including integrated solutions for heat management and hydrogen purification with a demonstration system, running for at least 500 hours and producing at least 10 kg H2/day at atmospheric pressure.
- Demonstration of scalability of the developed system to large-scale production (equivalent to the 100 t H2/day) for long distance transportation and a techno-economic analysis for the scalability for 1000 t H2/day.

Project examples : *H2Sektor / HRS Erlangen*[2]

Recommendation: The **EU** and/or **Member States** should consider **to allocate direct public funding to pioneers in the EU port areas** that are launching investments in R&I projects aiming at **advancing the technological maturity of industrial-scale LOHC dehydrogenation** near hydrogen carrier import terminals, and demonstrate their techno-economic feasibility (i.e., cost reduction, improved process efficiency, etc.)

Note: (*) Total cost attributable to a hydrogen carrier system to supply, on average, 1000 tpd of Hydrogen over a round trip distance of 3000 km, expressed on a per kg hydrogen delivered basis.

Sources: (1) Clean Hydrogen JU Work Programme 2022; (2) Hydrogenious LOHC Technologies; (3) VOPAK and Hydrogenious jointly take LOHC to next level; (4) Evos, Hydrogenious LOHC Technologies and Port of Amsterdam to jointly develop large-scale hydrogen import facilities | Port of Amsterdam.

Safety challenges and associated recommendations for the development of hydrogen carrier (ammonia and LOHC) conversion facilities in port areas

Overview of the safety challenge: An open and transparent communication of risk associated with using LOHC compounds and ammonia to the general public is a key in gaining social acceptance.

Objective: **Emission free ammonia and LOHC conversion facilities**

Where are we today: There are no generic safety regulations for ammonia or LOHC conversion facilities. Large scale ammonia crackers and LOHC dehydrogenation plants are not yet commercially available. Small and medium scale LOHC dehydrogenation and ammonia crackers units are commercially available.

Safety projects should focus on:

- Safety distances around the conversion terminal and external safety considerations.
- Considering the toxicity of ammonia and with that occupational safety, development of effective measures to minimize emission levels.
- Testing of the LOHC carrier that not only performs technically the best but also the carrier that is least toxic and most environmentally friendly.
- Ecotoxicological screening and environmental fate assessment of potential LOHC candidates and derive design criteria for better LOHC structures.

Recommendations:

- See recommendation 1 page 110 (recommendation to the EU and Member States)
- The EU should ensure the **development of emission regulations in the direct vicinity of the conversion facility (predominantly ammonia)**.
- The EU should support the **development of occupational health guidelines within the property boundaries for both ammonia and LOHC**.

Sources: not applicable.

Non-technical challenges associated with the development of **hydrogen carrier (ammonia and LOHC) conversation facilities in port areas**

Non-technical challenges hindering the **development of large-scale hydrogen carrier (ammonia and LOHC) conversation facilities in port areas:**

1. **Lack of industrial-scale ammonia cracking and LOHC dehydrogenation pilot projects** in the EU, encompassing broad partnerships between the public sector (CAPEX investment support) and industry (i.e., technology providers, investors, industrial consumers and logistics operators) to advance the technological maturity of these technologies and demonstrate their techno-economic feasibility (i.e., cost reduction, improved process efficiency, higher hydrogen purity).
2. **Lack of regulations, technical (including safety) standards, permitting procedures and operational guidelines for the construction and operation of ammonia cracking and LOHC dehydrogenation facilities**, which makes it difficult to access public fundings for the development of demonstration projects.
3. **Lack of bankability or financial viability of industrial scale ammonia crackers and LOHC dehydrogenation facilities**, mainly due to the high CAPEX required to develop these innovative technologies as well as the high energy consumption associated with the activity.
4. **Lack of available space in port areas to build new hydrogen carriers conversion infrastructure as well as associated equipment** (e.g., storage tanks for hydrogen carriers, compressor stations to compress hydrogen to the pressure required for injection in the pipeline).
5. **Lack of certainty as to when the willingness of potential end-users to purchase and use imported GH2 recovered from its hydrogen carrier will be higher than for direct purchase and use of the imported hydrogen carrier (e.g., ammonia)**[1].
6. **Lack of appropriate energy infrastructure (electricity cables, pipelines, etc.) to supply the large amount of energy (electricity and heat) required to in the conversion activities of LOHCs and ammonia to GH2**.

Notes: (1) As ammonia can be used as an energy carrier or feedstock in a variety of applications in the framework of the transition to a low-carbon economy (e.g., maritime fuel, feedstock for power generation, chemicals), it could potentially make sense not to convert ammonia back into hydrogen. However, the transport of ammonia has substantial regulatory requirements, due to its toxicity for human health and the environment. For instance, ammonia transport via road freight is usually not allowed in the EU, except when the shipment is declared as a dangerous goods transport (in that case, transportation load is restricted to 13-57k liters. Currently, ammonia is usually transported via railway with a pressure level of 12 bar in liquid form, declared as a dangerous goods transport. The capacity of these tank cars on railways is approx. 130,600 liters.

Source : IRENA, 2022; Fraunhofer ISI, 2022

Recommendations for addressing non-technical challenges related to the development of **hydrogen carrier (ammonia and LOHC) conversation facilities**

Responsible authority(ies)**: Port authorities and other port stakeholders**

1. In those European ports that will develop additional large-scale hydrogen carrier (ammonia or LOHC) import capacity, **port stakeholders** (including port authorities, terminal operators, energy storage companies, pipeline operators, and local industries) **should review and assess the societal relevance and techno-economic rationale of developing large-scale ammonia cracker or LOHC dehydrogenation projects**. To this end, port authorities should lead the development of feasibility studies to determine if and/or when hydrogen carrier conversion activities could be needed from a demand perspective (i.e., to determine how much of the imported ammonia would be used directly and how much of the imported ammonia would need to be converted back to hydrogen), as well as the techno-economic implications (e.g., on land-use planning and on electrical and thermal infrastructure) of developing these activities.

2. If the case for hydrogen conversion is found to be positive, **port authorities should take the lead, guide, and actively participate** (either as a project owner, landlord or project facilitator) **in consortia of companies to develop hydrogen carrier conversion projects before 2030**[1].

Responsible authority(ies)**: The European Union (EU) and Member States**

1. **The EU should work with** the relevant standardization authorities (i.e., **CEN, CENELEC**) **to develop prescriptive harmonized EU-wide regulations, including clear guidelines to Member States on administrative practices and permitting procedures, as well as technical, operational and safety standards** for **hydrogen carrier conversion facilities**.

Notes: (1) In particular, port authorities could facilitate and coordinate the development of hydrogen carrier conversion projects involving multiple port-related stakeholders or external parties by:

- **Identifying land areas** in the vicinity of the port that that would be suitable for the construction and operation of (large-scale) conversion facilities.
- **Promoting social and public acceptance** of hydrogen carrier conversion facilities among port-related stakeholders and local populations.
- **Providing support to identify and secure access to European and/or national public funding programmes**.
- **(Co-) investing in specific flagship demonstration hydrogen conversion projects** (i.e., ammonia cracking and LOHC dehydrogenation).
- **Ensuring the availability of basic operational services** necessary for the safe and efficient construction and operation of these conversion facilities.
- **Bringing together relevant public and private stakeholders** (e.g., hydrogen importers and hydrogen transporters to end-users in the hinterland).
- **Encouraging existing hydrogen-consuming and energy intensive industries to move towards a closer vicinity of the port**.

Multimodal land-based hydrogen refueling stations (HRSs)

Photo: Pinpoint clean fuels

Introduction: Multimodal land-based hydrogen refueling stations for inland shipping, short-distance maritime operations and port equipment machineries (fuel cells)

Description of the activity: Fueling/bunkering of (compressed) hydrogen for use as a fuel by inland shipping, short-distance maritime operations, port equipment machineries (cargo handling and terminal equipment) and road trucks at a land-based hydrogen refueling station comprising the following specific technical components: adequately sized storage facilities for hydrogen (to bring the hydrogen to the desired gas pressure level), a precooling system, and dispensers for delivering the fuel.

Context and background

- For compressed GH2 to play a role in enabling the complete decarbonisation of inland shipping, short-distance sea-going maritime applications (e.g., port fleet) and port equipment machineries (cargo handling and terminal equipment), **appropriate hydrogen refueling stations (HRS) will need to be constructed and operated in the vicinity of ports**.
- Even though many projects are currently aiming at improving HRS technologies to address the refueling needs of road freight heavy-duty vehicles[1], **land-based stationary compressed hydrogen refueling** (bunkering) **solutions for application in inland shipping, short-distance sea-going maritime applications and port equipment machineries is still at a low technological maturity level** (TRL 3), and the development of innovative refueling systems that can deliver hydrogen quickly and at low cost is needed.
- To this end, **multi-modal stationary refueling** (bunkering) **infrastructure**, which can supply compressed hydrogen to a range of land and sea-based vehicles (including inland and short-distance sea-going maritime vessels (pipe-to-ship), as well as cargo handling and terminal machineries), **are seen as promising solutions to enable simultaneous refueling operations in port areas**[2].
- In a context where the EU stimulates ports located along the TEN-T core and comprehensive networks to have an increased role in the supply chain of zero/low carbon fuels with accelerated deployment of refueling stations and in multimodal hubs where multiple transport modes could be supplied[3], **ports could play a role** in diversifying applications for hydrogen **by developing hydrogen refueling** (bunkering) **infrastructure that could be used for port equipment, road transport and inland/short-sea vessels**.

Prototype of a multimodal land-based hydrogen refueling (bunkering) station (source: link)

Notes: (1) Given that land-based HRS for supplying road freight heavy-duty vehicles is not a port-specific issue, this technological area is not in scope of this study; (2) According to Hydrogen Europe (2021), before that the distribution, storage and bunkering of compressed hydrogen can be upscaled, it is likely that, as a first step, small ships in ports will be supplied with hydrogen from hydrogen tube trailers and/or fixed compressed hydrogen tanks coming from hydrogen refueling stations on land (where hydrogen for other applications such as trucks, tractors, busses, etc. can be supplied as well); (3) See Articles 6 and 13 of the Commission proposal for an EU Regulation on the Deployment of Alternative Fuels Infrastructure (COM(2021) 559 final).

R&I challenges and associated recommendations for the development of hydrogen compression infrastructure

Description of the R&I challenge: Most commonly used technologies for hydrogen compression are based on mechanical compression and include reciprocating, diaphragm and centrifugal compressors. Currently available mechanical hydrogen compressors are too costly for large-scale applications and lack the desired durability, efficiency and reliability. This results in high operational and maintenance costs.

Objective: **Increase in compression performance of mechanical and non-mechanical compression**

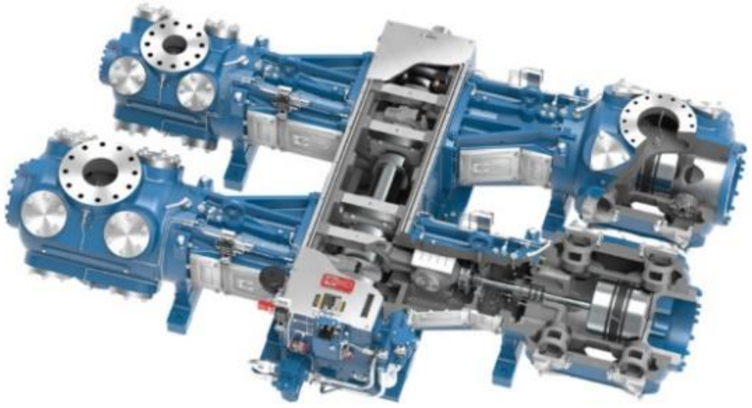
- **Target for 2030**: Technical lifetime < 20 yr; Energy Consumption < 3 kWh/kg*
- **Cost target in 2030**: OPEX <0,03 €/kg; CAPEX < 3500 €/kg
- **Research Timeline**: 2023-2030

Where are we today: Mechanical compressors are commercially available at main equipment suppliers such as Siemens, Neuman & Esser, Atlas Copco and Howden. Ionic compressors are commercially available at Linde[1].

Technical R&I aspects: The main challenges for hydrogen compression are leakage (through seals) and hydrogen embrittlement. In centrifugal compressors, the low molecular weight of hydrogen leads to low pressure ratios. This requires many compressor stages or high rotational speeds (which induces high stress in the impeller blades) to compensate. Alternative compression technologies are under development, such as electrochemical and metal hybrid compression systems.

R&I projects should focus on:

- Increase in efficiency, reliability, durability and available scale of alternative compression technologies.
- Increase in efficiency, reliability and maintainability of mechanical compression
- Material development for impellers able to withstand hydrogen embrittlement and stress induced by rotational speed



Horizontal type reciprocating compressor[2]

Recommendation: The **EU** and/or **Member States** should consider **to allocate direct public funding to organizations** that are launching investments in R&I projects aiming at **improving compression performance of mechanical and non-mechanical compression.**

Note: (*) Strategic Research and Innovation Agenda (page 160).

Sources: (1) Linde - Ionic compressor 50; (2) Tahan, M. - Recent Advances in Hydrogen Compressors

Safety challenges and associated recommendations for the development of land-based hydrogen refueling for inland shipping, short-distance maritime operations and port equipment machineries

Description of the safety challenge: Refuelling heavy duty port equipment, small maritime vessels (tug boats, barges) for in-port activities requires safe refuelling stations that have minimum impact on external safety and do not require adherence to the SEVESO III guidelines.

Objective: **Development of standards and protocols for refueling of in-port heavy duty vehicles and in-port maritime vessels.**

Where are we today: Based on the EU directive 2014/94 on alternative fuels infrastructure directive (AFID) standards are being developed (M533 and M581) for hydrogen supply to road vehicles and maritime transport. CEN/TC 268 developed three standards for road vehicles – EN17127 for refueling points, 17268 for refueling connection devices and 17124 for specifications of fuel cells[1]. For maritime applications mobile modular refueling systems will be used, in light of the SEVESO III guidelines.

Safety projects should focus on:

- Thermal effects on durability and integrity of storage tanks.
- The mechanical integrity of higher-pressure composite tanks (≥ 700 bar) for extended range.
- Safety distances of the (mobile) refueling station and crash mitigation measures especially for heavy duty vehicles.
- Ventilation requirements to avoid the accumulation of flammable atmospheres at (mobile) refueling station, location of appropriate detection systems and positioning of venting lines.

Recommendations:

- See recommendation 1 page 117 (recommendation to the European Union and Member States)
- The EU should **encourage the ISO to**
  - **develop standards and protocols for port equipment heavy duty vehicles and short distance maritime operations.**
  - **develop standards and protocols for compressed hydrogen refueling points for maritime and inland vessels**.
- The EU should support the development of **testing and certification protocols for unified hydrogen refueling connections, testing and verification.**

Sources:(1) European Clean Hydrogne Alliance, 2023

Non-technical challenges associated with the development of **land-based hydrogen refueling stations for inland shipping, short-distance maritime operations and port equipment machineries**

Non-technical challenges hindering the efficient, rapid and large-scale **development land-based hydrogen refueling stations for inland shipping, short-distance maritime operations and port equipment machineries:**

1. **Lack of port-specific roadmaps** developed by port authorities in collaboration with future hydrogen producers and users in the end-users in the port areas (i.e., inland shipping, short-sea maritime shipping, terminal operators for cargo handling activities) to precisely define key milestones and conditions for the development of multi-modal stationary refueling infrastructure (which can supply compressed hydrogen to a range of land and sea-based vehicles) in the port ecosystem (i.e., timing, quantities, end-users, required infrastructure, investment needs, etc.).
2. **Lack of clear administrative practices, guidelines and procedures** (i.e., permitting requirements) **for the development of HRSs in ports areas** (the permitting requirements applicable to HRSs currently drawing on obligations established at EU level, such as SEVESO Directive for risk assessments, the ATEX Directive for health and safety requirements and conformity assessment procedures, the Industrial Emissions Directive for integrated environmental obligations and the Strategic Environmental Assessment and the Environmental Impact Assessment Directives for environmental impact assessment procedures).
3. **Lack of standardization of the developed engineering solutions**, including components such as refueller, connections, nozzles, as well as of fueling protocols.
4. **Lack of sufficient certainty on future demand and supply availability of compressed hydrogen** for use as a fuel in inland and short-distance sea-going maritime vessels as well as cargo handling and terminal machineries, disincentivizing port areas to invest in HRSs (demand).
5. **Lack of financial incentives for port areas** to construct and operate HRSs, mainly due to the high CAPEX required to develop these innovative infrastructure.

Note: (1) SINTEF Energi AS, 2019

Recommendations for addressing non-technical challenges related to the development of **land-based hydrogen refueling stations for inland shipping, short-distance maritime operations and port equipment machineries**

Responsible authority(ies)**: Port authorities and other port stakeholders**

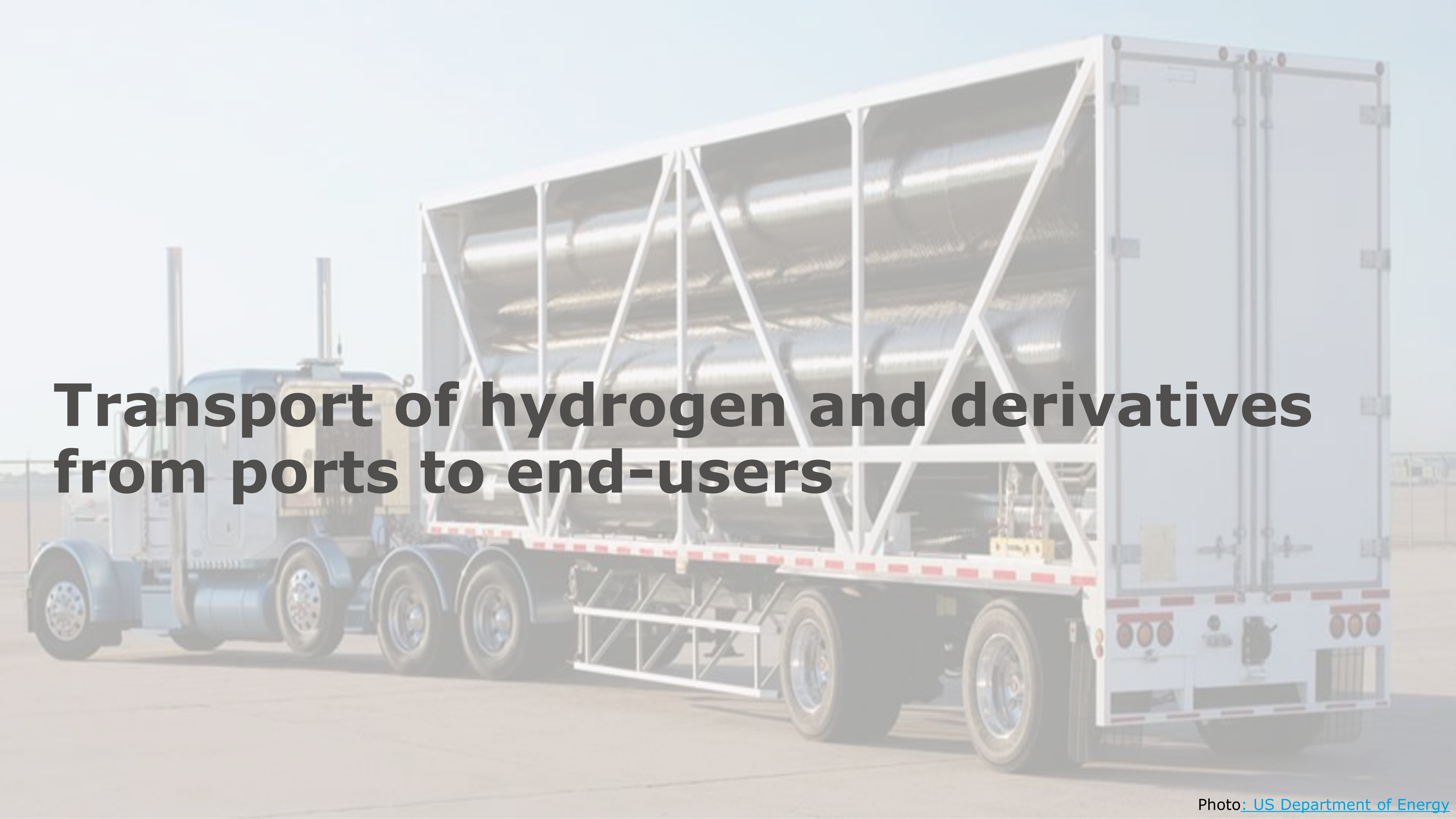
1 In line with the regulatory provisions established in the Alternative Fuels Infrastructure proposal (Article 13), and based on their **port-specific roadmap for the uptake of hydrogen/hydrogen-based maritime fuels in their areas** (see section '*Use of hydrogen and hydrogen-based fuels in the maritime sector*' - slides 66 to 74), **port authorities** should ensure that enough multi-modal stationary HRSs are made available to meet the future demand from both maritime (inland and short-distance sea-going maritime ships) and land-based (cargo handling and other terminal machineries, and heavy-duty trucks) vehicles. Should the **port authorities not have direct responsibility for the development and/or operation of HRSs**, they should **actively contribute to encouraging**, **stimulating**, or **compelling** (depending on the port's governance and regulatory powers) **relevant port-related stakeholders to timely develop and/or operate multi-modal stationary HRSs.** For instance, this incentivization could be done by:

- **Bringing together hydrogen producers**, **end-users** in the port areas (i.e., inland shipping, short-sea maritime shipping, terminal operators for cargo handling activities, road transport companies performing container loading/unloading operations) and **HRS manufacturers/operators**.
- **(Co-) investing in specific flagship demonstration projects** to prove the technical and economic feasibility of multi-modal stationary HRSs.
- **Providing support to identify and secure access to European and/or national public funding programmes**.

Responsible authority(ies): **The European Union (EU) and Member States**

1 **The EU should work with** the relevant standardization authorities (i.e., **CEN, CENELEC**) **to develop prescriptive harmonized EU-wide regulations, including clear guidelines to Member States on administrative practices and permitting procedures, as well as technical, operational and safety standards** for the **construction** and **operation** of **multi-modal stationary HRSs** in port areas.

2 To increase supply certainty, the EU could develop regulatory provisions **requiring all sea and inland ports** in the TEN-T core and comprehensive networks with **a significant flow** (e.g., above a defined threshold) **of road trucks and inland vessels performing loading/unloading activities to systematically install at least one multimodal HRS by 2030**.



Transport of hydrogen and derivatives from ports to end-users

Photo: US Department of Energy

Introduction: Road trucks, railways and inland barges could be used to bring hydrogen or hydrogen derivatives from port areas to end users

Description of the activity: Inland transportation of hydrogen (in a compressed or liquid form) and hydrogen carriers in truck trailers, trains and inland ships (barges) from port areas to various end users in the hinterland.

Context and background:

- Whether the product demand is for GH2, liquid hydrogen, or hydrogen derivatives (i.e., ammonia, LOHC, methanol), **transportation solutions will need to be developed to bring imported and/or locally produced hydrogen or hydrogen derivatives from port areas to various end users** in the hinterland. While the future pan-European hydrogen backbone[1] is expected to be the primary transport solution for moving (at optimum costs) hydrogen safely and in large quantities over long-distance from major European import terminals to the hinterland[2], other **complementary transport solutions may also need to be developed**, especially to provide hydrogen (derivatives) **in smaller quantities to end users not directly connected to hydrogen pipelines**. Various transportation solutions could serve this purpose[3]:
  - **Road truck**: Transport of hydrogen and hydrogen carriers on dedicated tube trailers that are placed on trucks are **mature technologies** (TRL 9 for LH2, ammonia, methanol and LOHC, and TRL 8 for GH2). Although **LH2 and GH2 tube trailers are not widely used in the EU yet**, the technologies are very close LNG/CNG tube trailers (already widely developed).
  - **Rail**: While the transport of ammonia, methanol and LOHC in dedicated tank wagon (specifically designed for one or more liquid commodities) **are mature technologies already widely used**, **LH2 and GH2 are not yet transported by rail** (no hydrogen transport containers are approved for train traffic yet[4]). However, no technical obstacles have been identified and some companies are currently developing dedicated solutions for liquid and compressed hydrogen transport by rail[5].
  - **Inland barges**: As with rail transport, the transport of ammonia, methanol and LOHC by inland barges is a **common activity already carried out in the EU**. However, **hydrogen (in compressed or liquid form) is not currently transported by barges on EU inland waterways**. The technologies should however be similar to those used for transportation via road trucks (compressed gas cylinders or cryogenic liquid tankers)[6].

Transporting hydrogen via inland waterways on barges[7]

Notes: (1) The European Hydrogen Backbone (EHB) initiative; (2) Since decisions related to the construction of hydrogen pipelines or to the retrofitting of existing fossil gas pipelines are taken by Member States governments (through their respective Transmission and Distribution System Operators), and that port authorities and other port-related stakeholders are generally not the owners of the pipeline infrastructure, it is not expected that port authorities and related stakeholders will play a significant role in developing the future EU hydrogen pipeline network system. Therefore, the activity consisting of transporting hydrogen through pipelines from the place of production to the place of consumption is not further investigated in this study; (3) Even though long-distance transport of ammonia via pipeline constitutes a potential option and is a proven technology (i.e., a 4,830 km carbon steel pipeline network is already used in the United States to transport ammonia from port and production facilities to agricultural areas for use as a fertilizer), this activity is not yet developed in Europe and it's development would require the establishment of a comprehensive EU regulated framework. For the same reasons as for hydrogen pipelines, ammonia pipeline is not further investigated in this study; (4) pv magazine, 2022; (5) For instance, in Germany, the company DB Cargo is developing rail transportation solutions for hydrogen to bring the hydrogen easily and efficiently from the ports to the consumers in the hinterland (see: pv magazine, 2022 or DB Cargo); (6) Hydrogen Europe, 2021; (7) link. **Sources**: Institute of Sustainable Process Technology, 2019 (pages 136 to 231); EnTEC, 2022.

R&I challenges and associated recommendations for the transport of hydrogen by truck and rail

Description of the R&I challenge: Transportation of hydrogen by truck and rail is a mature market. **Hydrogen** (in compressed or liquid form) **is not currently transported by barges on EU inland waterways**. The technologies should however be similar to those used for transportation via road trucks (compressed gas cylinders or cryogenic liquid tankers).

Objective: **Improve the efficiency and capacity of liquid and compressed hydrogen transport**

- **Target for 2030**: Tube trailer payload of 1500 kg and operating pressure of 700 bar[1]; LH2
- trailer payload 4000 kg[1] and boil-off 0,1%/day
- **Cost target in 2030**: Tube trailer CAPEX 350 €/kg[1]; LH2 tank trailer CAPEX 100 €/kg
- **Research Timeline**: 2023-2030

Where are we today: Current tube trailers deliver small quantities of compressed hydrogen gas (up to 300kg of hydrogen per delivery) at a low pressure (up to 300 bar). LH2 tank trailer payload capacity of 3500 kg and LH2 tank trailer boil-off 0,3 to 0,6%/day.

Technical R&I aspects: Compressed hydrogen can be transported in gas cylinders or gas tubes with pressures between 200 and 500 bar, usually several cylinders or tubes are used. Typically, the high weight of the cylinders or tubes limit the maximum hydrogen load that can be transported. Liquid hydrogen transported requires insulated tanks to reduce boil-off due to heat ingress.

R&I projects should focus on:

> Development of standardized inspection and repair methods that can be used to increase the lifetime of hydrogen storage.
> Development of multifunctional materials, focusing on reducing the whole life cost of hydrogen storage solutions.
> New lighter tubes manufactured with/without liners of improved performance materials (high strength alloyed steel, stainless steel or polymeric material) in combination with improved reinforcement (composite), in order to increase the pressure conditions, reducing the weight of the tube and assuring the requested safety levels and durability.
> Development of novel insulation concepts, reducing manufacturing cost whilst maintaining low boil-off rates for liquid hydrogen.

Transporting hydrogen via inland waterways on barges[3]

Recommendation: Building on the ZEWT partnership and the Clean Hydrogen Partnership, the EU and/or Member States should consider to allocate direct **public funding to R&I projects** aiming at **demonstrating the techno-economic feasibility of safely transporting LH2 and GH2 by barges**.

Note and Sources: (1) Strategic Research and Innovation Agenda (page 159); (2) To transport hydrogen either as a compressed gas or cryogenic liquid, advanced materials are required to withstand pressure or prevent heat ingress. These material requirements affect cost and mass, and lower cost and lighter solutions should be developed hydrogen technologies to be adopted widely; (3) link

R&I challenges and associated recommendations for the transport of hydrogen derivatives* by truck, rail and ship

Description of the R&I challenge: Ammonia is currently transported as a pressurised liquid in the fertilizer industry. LOHCs can be transported in conventional liquid bulk equipment.

Where are we today: Ammonia transportation is a proven technology, and the bulk supply chain is already in place at large scale.

Technical R&I aspects: Liquid ammonia is relatively safe in terms of flammability but is highly toxic and transport should meet specific regulations. Ammonia is typically transported under pressure or refrigerated. Ammonia can be transported by truck in semi-trailers or ISO-tank containers. Both store ammonia under pressure typically between 26-29 bar at atmospheric temperature[1]. For inland shipping, ammonia is stored in large cylindrical (semi-)refrigerated vessels. LOHC is a diesel-like substance and can easily be stored in conventional steel tanks. Therefore, practically all current storage systems for diesel or other oil like substances can be used for storage of LOHC. This means that existing infrastructure such as bunker ships, semi-trailers or ISO containers fitted with a steel tank can be used[1].

R&I projects should focus on: No R&I challenges associated with the development of transport solutions for hydrogen derivatives by truck, rail and ship have been identified.

Tanker truck used by Hydrogenious for LOHC transport[2]

Ammonia transportation via rail[3]

Ammonia transportation via inland barges[4]

Recommendation: No technological barriers identified

Notes: (*) This analysis focuses on ammonia and LOHC as the main hydrogen carriers, other carbon-based fuels and solid carriers are relevant but outside the scope of this analysis.
Sources: (1) RH2INE - Hydrogen Containment Systems; (2) Hydrogenious demos LOHC supply chain; (3) Ammonia transportation via rail; (4) Ammonia transportation via inland barges

Safety challenges and associated recommendations for the development of **hydrogen and derivatives transportation solutions from ports to end-users**

Description of the safety challenge: The large-scale transport of hydrogen and hydrogen carriers from the port to the users will traverse through inhabited areas for which safety needs to guaranteed.

Objective: **Establishing a set of standards and guidelines for the large-scale transportation of hydrogen and hydrogen carriers via trucks, rail tankers and inland navigating vessels**

Where are we today: ISO 11114 standard on the compatibility of cylinder and valve materials with gas contents with focus on hydrogen embrittlement[1]. Standards are available on the transport and storage of hydrogen in composite cylinders (EN17339) and steel cylinders (EN 13322), as well as cylinder bundles for the transport of permanent and liquified gases (EN13365)[2]. Methanol and ammonia are common feedstock in chemical industry and are transported by rail and pipeline (predominantly ammonia)**.**

Safety projects should focus on:

- Mechanical integrity of light composite tanks for higher pressure hydrogen (≥ 700 bar) transport.
- Embrittlement (gaseous hydrogen)/corrosion (ammonia) of steel pipes leading to leakages.
- Leakage mechanisms of valves and other devices in rail tankers and trucks for hydrogen and ammonia.
- Blast effects of accidentally formed flammable cloud in relation to external safety (rail tankers, trucks).
- Compatibility of materials in contact with hydrogen/hydrogen carriers under the influence of repeated cycling (pressure, temperature).

Recommendations:

- See recommendation 1 page 124 (recommendation to the European Union and Member States)
- See recommendation 2 page 124 (recommendation to the European Union and Member States)
- The EU should **encourage the ISO to include LOHC in ISO 15916** (consideration for the safety of hydrogen systems).
- The EU should **encourage the ISO to adapt the current standards on LNG to liquified hydrogen and compressed/refrigerated ammonia**.
- The EU should support the development of testing and certification protocols for **steels resistant to hydrogen embrittlement**.

Sources: (1) European Clean Hydrogen Alliance, 2023; (2) Sandana et al., 2021

Non-technical challenges associated with the development of **hydrogen and derivatives transportation solutions from ports to end-users**

Non-technical challenges hindering the **development of hydrogen and derivatives transportation solutions from ports to end-users:**

1. Given that LH2 and GH2 are not yet transported by rail (no hydrogen transport containers are approved for train traffic yet), **no clear and harmonized safety regulations and permitting procedures for LH2 and GH2 transportation by rail have been established** (both at the EU and Member States level)[1].
2. Given that LH2 and GH2 are not yet transported by inland barges, **no clear and harmonized safety regulations and permitting procedures for LH2 and GH2 transportation in inland shipping have been established** at the EU level**.**
3. Even though handling (loading, transporting, unloading) of hazardous chemical substances via road, rail or inland waterway is an already widely-developed practice in the EU[2], and that ammonia transport is under strict safety regulations[3], the inland transportation of ammonia in the EU faces a negative public perception, reinforced by the fact that road freight, rail and inland shipping transport often passes close to residential areas. **The further development of ammonia transportation via road trucks, trains and barges at a larger scale is therefore likely to face social and public reluctance**.
4. There is a general **lack of understanding on the which transport mode** (road truck, railway or inland shipping) **is most economically competitive for LH2 and GH2**[4].
5. **Compressed hydrogen gas storage in tanks is currently highly expensive** (compared to the transportation of hydrogen in liquified form or as a hydrogen carrier)[5].

Sources: (1) Royal HaskoningDHV, 2022; (2) For instance, every year more than 1.5 Mt of ammonia is transported in Western Europe by rail (Fertilizer Europe, 2019); (3) DIRECTIVE 2008/68/EC on the inland transport of dangerous goods; (4) pv magazine, 2020; (5) EnTEC, 2022

Recommendations for addressing non-technical challenges related to the development of **hydrogen and derivatives transportation solutions**

Responsible authority(ies)**: Port authorities and other port stakeholders**

1 In close collaboration with hydrogen or hydrogen carrier suppliers, owners of small-scale storage infrastructure (i.e., tube trailers for LH2 or GH2), and road and/or rail and/or inland barges transportation companies, **port authorities** that will host hydrogen and hydrogen carriers import and/or hydrogen production activities **should ensure the availability of land surfaces as well as basic operational services necessary for the safe and efficient loading of hydrogen or hydrogen derivatives** (in gaseous or liquid form) **onto road tube trailers and/or tank cars and/or inland barges**.

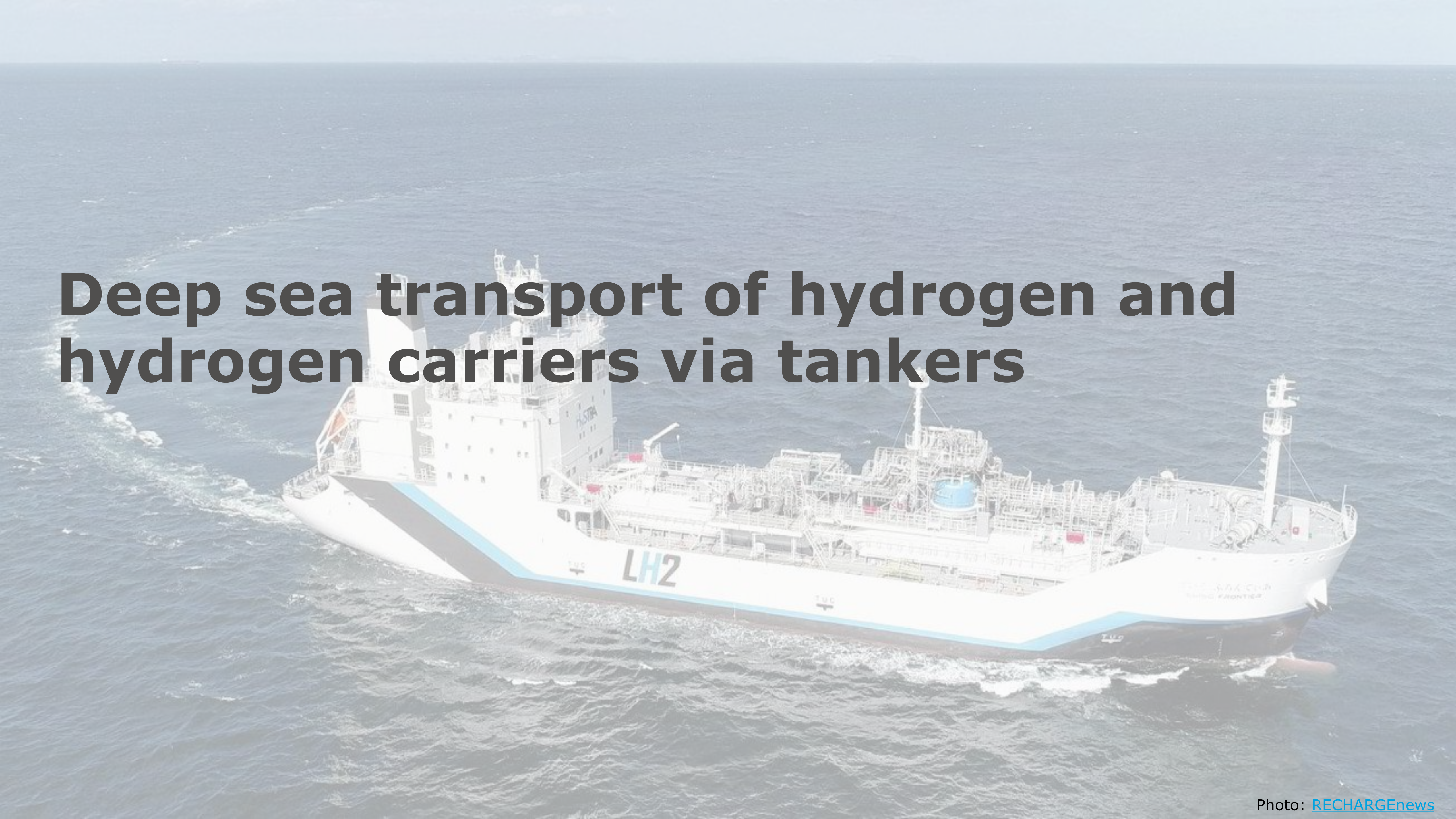
2 Port authorities could also contribute to **promoting social and public acceptance** of hydrogen and ammonia transport activities among port-related stakeholders and local populations.

Responsible authority(ies)**: The European Union (EU) and Member States**

1 **The EU should work with** the relevant standardization authorities (i.e., **CEN, CENELEC**) **to develop prescriptive harmonized EU-wide regulations as well as technical, operational and safety standards** for **the transportation of GH2 and LH2 by rail** in the EU.

2 Building on the lessons learned from the experiences of transporting LNG on ships, on the IMO's "*Interim recommendations for carriage of LH2 bulk*" of the IGC Code International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk, and on the guidelines published by the classification society ClassNK for the safe construction and operation of LH2 carriers, the **EU should work with** the relevant regulatory and standardization authorities (i.e., **CESNI, CCNR) to develop prescriptive technical regulations, including clear guidelines to Member States on administrative practices and permitting procedures, as well as technical and safety standards for the transportation of hydrogen on inland waterway vessels**.

Hydrogen and hydrogen carriers-related activities and infrastructure **in the wider setting of the port areas**



Deep sea transport of hydrogen and hydrogen carriers via tankers

Photo: RECHARGEnews

Introduction: Ports can facilitate the development of large-scale seaborne commercial transportation (in tankers) of hydrogen and hydrogen carriers

Description of the activity: Seaborne commercial transportation (in tankers) of hydrogen in the form of compressed hydrogen (GH2), LH2 (LH2), ammonia , LOHC or methanol (CH_3OH).

Context and background:

- While onshore or offshore pipelines are expected to be used to transport hydrogen up to a distance of 2,500-3,000 km, seaborne transportation may be the least costly choice for longer distances[1]. Hydrogen can be transported as **compressed** (GH2) **or LH2** (LH2)[2], as **ammonia**, as a **LOHC** or as synthetic hydrocarbon-based molecules (e.g., methanol).
- On the one hand, **commercial seaborne transportation of ammonia, LOHC and methanol is a mature technology** (although it may need to become larger and more flexible). On the other hand, **transporting compressed or LH2 in ship tankers faces a lack of technology readiness levels**, requiring an accelerated investment and innovation effort to bring the technologies to a commercial stage at the scale needed in the next decade[3].
- As of early 2023, the Hydrogen Energy Supply Chain (HESC) project in Australia is the **first demonstration facility to test hydrogen (in LH2 form) shipping**. It integrates a hydrogen liquefaction facility (0.25 tpd), a LH2 storage container (41 m3) and a loading facility in Victoria. **LH2 is transported to Japan in the world's first LH2 tankers, Suiso Frontier**, with a capacity of 1 250 m3 (75 tonnes of LH2 per trip) and double-shell vacuum insulation tanks[4]. The first shipment of LH2 arrived at the receiving terminal HyTouch Kobe in Japan in February 2022[5].
- In parallel, **various companies are working on the design of the first commercial liquefied[6] and compressed[7] hydrogen as well as LOHC[8] tankers**.

Liquid hydrogen tanker design from C-Job Naval Architects LH2 Europe[9]

Notes: (1) IEA, 2022; (2) The transport of hydrogen in the form of GH2 and LH2 may be attractive for users requiring high purity hydrogen; (3) Roland Berger, 2021; (4) Kawasaki, 2021; (5) HySTRA; (6) *KHI* has received approval in principle from the classification society ClassNK for a large LH2 tanker of up to 160 000 m3 (approximately 10 kt of H2 per trip), with a propulsion system that can use hydrogen (see Kawasaki, 2022); *C-Job Naval Architects* in partnership with *LH2 Europe* are planning to build a 37 500 m3 LH2 tanker powered by hydrogen fuel cells (expected to be available by 2027) (see C-Job Naval Architects); *Korea Shipbuilding & Offshore Engineering* and its shipyard *Hyundai Mipo Dokyard* have received an approval in principle to build a LH2 tanker of 20 000 m3 (expected to be ready between 2025 and 2027) (see g-Captain, 2022); In July 2022, *GTT* (a technology firm for design of cryogenic containment systems used to store and transport liquefied gases) and *Shell International Trading and Shipping Company*, received two approval in principles from the ship classification society DNV for the design of a membrane-based LH2 containment system and for the preliminary concept design of a LH2 tanker (see GTT, 2022); (7) *Australian Provaris*, (formerly *Global Energy Ventures*), received an approval in principle in 2021 from the American Bureau of Shipping for a compressed hydrogen pilot tanker with a 430 tonne cargo capacity at 250 bar (26 000 m3) and for a full-scale 2 000 tonne tanker (see Small Caps, 2021); Norwegian companies, *Gen2 Energy and Sirius Design & Integration*, are working on the design of a tanker to transport containers with compressed hydrogen, using hydrogen as fuel (about 500 containers, resulting in around 30 000 m3)(see Gen2 Energy, 2022); (8) The Advanced Hydrogen Energy Chain Association for Technology Development (AHEAD) project in 2019 commissioned a hydrogenation demonstration facility in Brunei Darussalam to transport hydrogen as methylcyclohexane (MCH) to a gas turbine at the TOA Oil Co Keihin refinery in Japan (May 2020). MCH was dehydrogenated to separate hydrogen and toluene, the latter being shipped back to the exporting terminal, so that it could be used again as a hydrogen carrier. MCH was transported in 24-m3 ISO tank containers mounted on container ships. The project demonstrated the technology of producing and consuming hydrogen using a LOHC for transportation (see Chiyoda); (9) C-Job Naval Architects LH2 Europe

R&I challenges and associated recommendations for the transportation of liquid hydrogen by ships

Description of the R&I challenge: Shipping of LH2 will represent a flexible means for transport of larger quantities of hydrogen over longer distances, as well as for regional distribution without a gas grid. However, large-scale solutions for the storage and bulk transportation of liquid hydrogen are in their infancy. In order to enable safe, cost- and energy efficient transport of bulk LH2 at energy system scale (in the order of GW hydrogen energy flux), large-scale LH2 ship storage concepts need to be developed for shipping of LH2[1].

Objective: **Design a scalable, large-scale LH2 storage tanker of the order of those used for LNG deep-sea transport today** (e.g., 200,000 m3 per ship), distributed between a relevant numbers of storage tanks. Such a capacity will correspond to 14,000 tonnes of hydrogen transported per ship.

- **Target for 2030**: LH2 ship containment tank capacity > 2800 tons
- **Cost target in 2030**: LH2 ship tank CAPEX <10 Euros/kg LH2
- **Research Timeline**: 2023-2028

Where are we today: The currently demonstrated size for LH2 containment for shipping is about 1,250 m3 (i.e., corresponding to 90 tonnes of hydrogen). Multiple European technology providers have started to design and develop LH2 containment solution*. Suiso Frontier delivered world's first cargo of LH2 to Japan[3].

Technical R&I aspects: Due to the considerably lower temperature of LH2 than LNG, as well as the lower heat of vaporization and different material compatibility characteristics, totally novel insulation concepts need to be developed if LH2 should be contained with equally or lower boil-off rate as current LNG concepts.

R&I projects should focus on:

> Concept selection for large-scale LH2 containment to be used in shipping and Approval in Principle (AIP) for the LH2 containment concept by one of the major IACS classification societies.
> Materials and component selection and integrity testing for LH2 exposure (e.g., strength, ductility, toughness, thermal expansion, sloshing and compatibility) and sub-system testing for thermo-mechanical validation.
> Detailed design, construction, and testing of a scaled-down prototype of at least 10t LH2 capacity.
> General approval for the LH2 containment system by one of the major IACS classification societies.
> Development of a preliminary integrated ship design with a corresponding cost estimation.

World's first LH2 deep-sea tanker[2]

Recommendation: The EU and/or Member States should **consider to allocate direct public funding to pioneers in the EU port areas that are launching investments in R&I and market-ready projects aiming at demonstrating or decreasing the cost of large-scale deep-sea ocean-going tankers for the seaborne transport of hydrogen (GH2 and LH2)**.

Notes: (*) e.g., based on the IMO Type B, Type C and membrane tank designs currently available for LNG shipping, as well as for other novel concepts.
Sources: (1) Clean Hydrogen JU Work Programme 2022 (page 95); (2) Kawasaki, 2021; (3) Suiso Frontier.

R&I challenges and associated recommendations for the transportation of hydrogen derivatives by ships*

Description of the R&I challenge: Ammonia is a widely traded chemical commodity that has long been transported in liquefied petroleum gas (LPG) tankers, which are also able to carry ammonia. LOHCs can be transported in conventional liquid bulk tankers.

Where are we today: Ammonia transportation is a proven technology and the bulk supply chain is already in place at large scale. The AHEAD program transported methylcyclohexane overseas for the specific purpose as an LOHC using the Crane Uranus, a conventional chemical tanker[1].

Technical R&I aspects: Ammonia transport by ship depends on storage conditions, which can either be fully refrigerated (ambient pressure/-50C), semi-refrigerated (4-8 barg/-10C) and under pressure (17 barg/45C). Ammonia is typically transported in gas carriers designed for liquid petroleum (LPG), designed according to the requirements of the 2014 International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) transportation. LOHC can be transported in chemical tankers due to its diesel-like characteristics.

R&I projects should focus on: No R&I challenges associated with the development of hydrogen carriers' transportation solutions by ships have been identified.

Crane Uranus, conventional chemical tanker used to transport LOHC[2]

Recommendation: No technological barriers identified

Notes: (*) This analysis focuses on ammonia and LOHC as the main hydrogen carriers, other carbon-based fuels and solid carriers are relevant but outside the scope of this analysis;

Sources: (1) Hydrogen transportation in the form of MCH by chemical tanker; (2) CRANE URANUS

Safety challenges and associated recommendations for the transportation of liquid hydrogen by ships

Description of the safety challenge: The storage and handling of liquid hydrogen in vessels that are capable of withstanding severe and frequent temperature swings, place constraints on the marine environment compatible materials of choice and on construction designs and methodologies to ensure its safe transportation on sea going vessels, to avoid the generation of large flammable clouds due to boil-off, planned venting or incidental leakages.

Objective: **Development of an international standard on the transport of liquid hydrogen by sea going vessels.**

Where are we today: The IGF code (IMO MSC 95/22/Add.1) is the main standard used for the shipping of gases and other low flashpoint fuels and hence applicable for hydrogen and most other hydrogen carriers (except some LOHC)[1]. Standard is based on LNG and considered appropriate for LH2 in absence of alternatives. There is only one liquid hydrogen vessel in operation (Suiso Frontier)[2], considered as a demonstration vessel. ISO/AWI 13985 International standard on the construction of refillable liquid hydrogen tanks for land vehicles can be used as a starting point[3]. Occupational hazards of liquid hydrogen as a substance well understood.

Safety projects should focus on:

- Prevention of safety risks due to the condensation of air (nitrogen and especially oxygen); specifically of importance in case of unintentional release of liquid hydrogen to prevent clogging, the formation of flammable atmospheres and burns of people in the vicinity of the cold spots.
- Establish appropriate safety distances between pressure relief valves (boil-off) and air inlets (ventilation).
- Design specifications and selection of materials for tanks carrying liquid hydrogen to for instance ensure resistance to hydrogen embrittlement, mechanical integrity to allow for severe and frequent temperature swings and appropriate thermophysical properties at cryogenic temperatures.
- Alternative/improved insulation technologies to supplement the current vacuum technique to avoid boil-off, especially in a port environment.
- The development of better models to predict the consequences of accidental spillage/leak of liquid hydrogen, especially at the initial phase of pool spread of vaporization.

Recommendations:

- See recommendation 1 page 132 (recommendation to maritime classification societies and associations)
- See recommendation 1 page 132 (recommendation to the European Union)
- The EU should support the **development of checklists and procedures for the safe mooring of sea going vessels within a harbor environment in light of the required safety distances around the ships due to boil-off**.
- The EU should support the **development of testing and certification protocols for for testing materials in direct contact** (and experiencing frequent temperature swings) **with LH2**.

Sources: (1) European Clearn Hydrogen Alliance, 2023; (2) The Suiso Frontier, (website) ; (3) ISO ISO/AWI 13985

Non-technical challenges associated with the development of **large-scale seaborne transportation of hydrogen and hydrogen carriers**

Non-technical challenges hindering the efficient, rapid and large-scale **seaborne transportation of hydrogen and hydrogen carriers**

1. **Lack of clear and harmonized international technical regulatory standards and guidelines** (e.g., risk-based processes) **in the processes for building** (deep) sea/ocean-going **LH2 and GH2 tankers**, resulting in lengthy and costly procedures to obtain the administrative authorizations necessary to construct and operate these new vessels[1]. **Note**: As GH2, LH2 have never before been envisaged as a regular bulk cargo to be carried at sea, hydrogen has not been included in IMO's IGC code[2].
2. **Lack of bankability or financial viability** of LH2 and GH2 tankers, mainly due to the high CAPEX required to develop these innovative hydrogen tankers[3].
3. **Lack of sufficient demonstration projects in European and national R&I programs** to demonstrate the technico-economic feasibility of transporting large quantities of compressed hydrogen (GH2) and LH2 (LH2) via seaborne commercial transportation (in tankers)[3].
4. **Market uncertainties on which future hydrogen form** (GH2 or LH2) **or hydrogen carrier** (ammonia, LOHC, methanol) will be the most competitive economically (before and/or after potential policy intervention) **for seaborne commercial transportation**, resulting in high reluctance from shipbuilders and shipping companies to launch demonstration projects[5].

Notes: (1) The International Convention for the Safety of Life at Sea ("the Convention"), 1974 and the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk ("the IGC Code") currently do not specifically provide requirements for carriage of LH2 in bulk by sea. However, in order to facilitate the development of the pilot project "Suiso Frontier", which has been developed for the research and demonstration of safe long-distance overseas carriage of LH2 in bulk, the IMO adopted in 2016 the "Interim Recommendations for carriage of LH2 in bulk". The IMO also committed to acquire information on safe carriage of LH2 in bulk prior to amendment to the IGC Code for the inclusion of LH2 (see RESOLUTION MSC.420(97)). Based on these IMO interim recommendations, the classification society ClassNK published the guidelines for LH2 carriers for the safe construction and operation of LH2 carriers (see ClassNK); (2) With respect to LOHC transport via tankers, although the 2019 AHEAD program (see Chiyoda) was the first-ever demonstration of hydrogen transport using LOHC (methylcyclohexane - MCH), the technology itself is a mature technology already addressed by international rules, although the applicable regulations are different depending on the type of LOHC used. For example, the maritime transport of LOHC methylcyclohexane (MCH) using ISO tank containers on Type 3 chemical tankers is regulated by Annex II of MARPOL 73/78 and the International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk (IBC Code). As another example, the maritime transport of LOHC hydrogenous Dibenzyltoluene (DBT) is not regulated as a dangerous good and therefore does not fall in the scope of Annex II of MARPOL 73/78 and the IBC code, meaning transportation of this compound does not require a chemical tanker (type 1, 2 or 3) and can be transported in any liquid tanker (see link); (3) Offshore Energy, 2022; (4) As of 2022, the 37,500 m3 LH2 tanker concept (expected to be available by 2027) developed by C-Job Naval Architects and LH2 Europe is the only European-based R&I project aiming at developing tankers capable of transporting large amount of hydrogen. The main technical challenges has to do with designing on-board tanks with appropriate size (GH2, LH2 and LOHC storage requires a lot of volume); (5) This barrier is of particular importance in the shipping sector as, given the very long lifespan of ship tankers, ship owners are very reluctant to invest in the construction of new alternative fuels tankers as long as they are not guaranteed sufficient demand for these ships in the long term, in order to avoid the risk of stranded assets.

Recommendations for addressing non-technical challenges related to the development of **seaborne transportation of hydrogen and hydrogen carriers**

Responsible authority(ies)**: Maritime classification societies and associations**

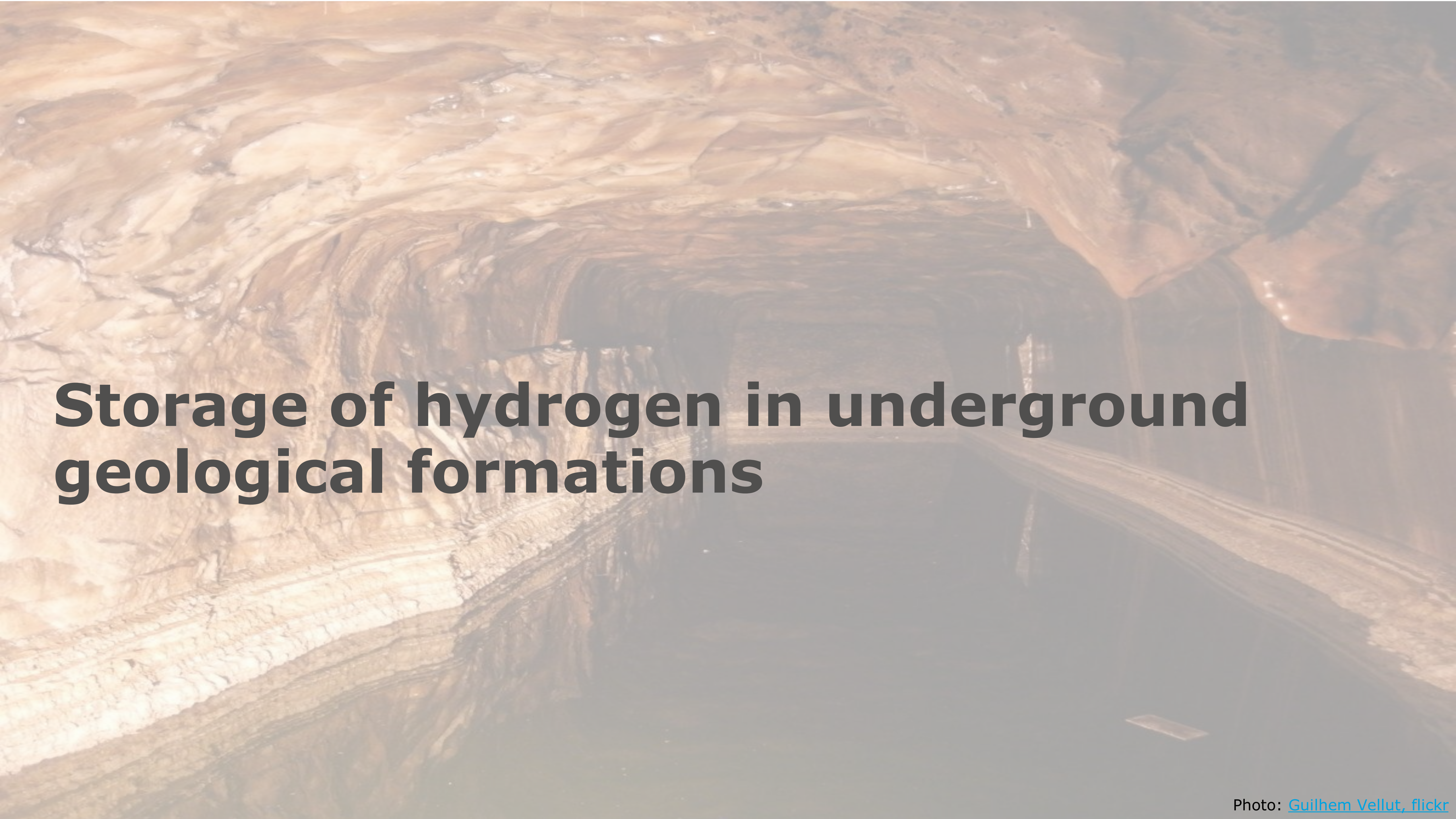
1 Pending the development of IMO and ISO technical regulatory standards, **relevant stakeholders (e.g., classification societies[1])** could build on the experience acquired in monitoring the operation of existing pilot projects (e.g., the Suiso Frontier) and align themselves to **establish one harmonized risk-based "alternative design" approval procedure** for the development and operation of new **tankers for maritime hydrogen (GH2 and LH2) transport**.

Responsible authority(ies)**: The European Union (EU)**

1 Building on the lessons learned from the experiences of transporting LNG in seaborne tankers[2], as well from the ISO/AWI 13985 and from the chemical process industries, on the IMO's "*Interim recommendations for carriage of LH2 bulk*" of the IGC Code International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk, and on the guidelines published by the classification society ClassNK for the safe construction and operation of LH2, **the EU** (through its most active/influential Member States) **should encourage the** IMO **to develop prescriptive harmonized international regulations**, **as well as technical and safety standards** for the **sea-based transportation** of hydrogen. In parallel, **the EU should encourage the** ISO to **revise the relevant ISO standards linked to the relevant IMO's Codes**.

2 **EU policies and funding programs** that aim at accelerating the decarbonization of the shipping sector and the import of hydrogen and hydrogen carrier to the EU **should be tailored to support the design, construction and retrofitting** of hydrogen and hydrogen carrier **tankers and** associated **maritime equipment by EU companies** over non-EU companies[3].

Notes: (1) When the Suiso Frontier trade was planned, the classification society SIGTTO played an integral part with the class societies in drawing up the the "Interim Recommendations for carriage of LH2 in bulk"; (2) The European Industrial Gases Association (EIGA) document 06/19 defines the regulation for layout, location, safety distances, and other elements for LNG terminals; (3) For instance, appropriate policy provisions should ensure that EU and public fundings aimed at developing new tankers for the seaborne transport of hydrogen support projects that are entirely conducted in Europe so that technical and technological capabilities built in the framework of these projects remain the ownership of European organizations.



Storage of hydrogen in underground geological formations

Photo: Guilhem Vellut, flickr

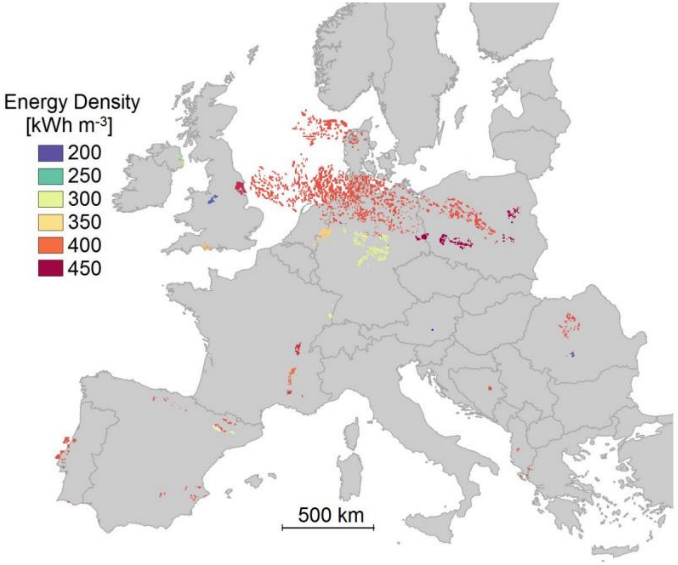
Introduction: Major seaports located along the North Sea could facilitate the transport of GH2 to permanent storage deep offshore

Description of the activity: Storage of hydrogen in underground geological formations (i.e., salt caverns, aquifers and depleted oil and gas fields) for large-scale cyclical and seasonal storage.

Context and background:

- Deploying hydrogen storage contributes to the system in terms of flexibility, supply security and economic value (Optimal/cost-effective development of network infrastructure)[1].
- Large technical potential for subsurface hydrogen geological storage (e.g., salt caverns and, potentially, depleted gas fields) exists in Europe, sufficient to meet future storage needs[2].
- The availability of storage site in salt caverns is limited to some member states[3], with **most of the potential located offshore, mainly in the North Sea**[4]. Germany and Netherlands have the highest storage potential in both onshore and offshore locations. **While storage of hydrogen in salt caverns is a proven technology (TRL 9), fast cycling of those storages is less mature (TRL 7)**[5].
- Depleted gas fields are more widely distributed across Europe than salt caverns and technical storage capacity across the EU is most likely to be very large, although currently not quantified[6]. **Storage of pure hydrogen in depleted fields and aquifers is not mature** (around TRL 3)[7] and largely depends on site-specific investigation.
- According to a first order estimate by Gas Infrastructure Europe (GIE), applying a storage to demand ratio of 24%[8], the hydrogen storage capacity estimate for 20 EU countries (excluding UK) shows the potential need for around 65 TWh of hydrogen storage in 2030, growing to around 410 TWh of hydrogen storage in 2050[9;10].

Major seaports with hydrogen/hydrogen carrier import terminals located along the North Sea can facilitate the transport of GH2 to permanent storage deep offshore. However, port authorities and other port-related stakeholders are **likely to play a limited role in activity related to the storage of GH2 in underground storage** as it is expected that hydrogen supply subject to seasonal storage will flow from pipelines to these geological reservoirs, with little or no intervention from port stakeholders[11].



Distribution of potential salt cavern sites across Europe with their corresponding energy densities[12]

Notes: (1) EnTEC, 2022; (2) Caglayan et al., 2020 ; (3) Nine Member States (DE, DK, EL, ES, FR, NL, RO, PL, PT) have a storage potential within 50 km from shore of more than 21,000 TWh (EnTEC, 2022); (4) The total technical potential of salt caverns in Europe is estimated at approximately 85 PWh of hydrogen, with only an estimated of 23 PWh (or 27%) of hydrogen storage potential located on onshore areas (EnTEC, 2022); (5) Examples of ongoing projects focusing on GH2 subsurface storage in salt caverns: Project Teesside in the UK (3 salt caverns, 70,000 m3 each, 370 m), Project H_2Cast Etzel in Germany (currently in the preparation phase, timeline 2022-2026), Project HyStock in the Netherlands, Project Hypster in France; (6) This is part of ongoing work in the HyUsPRe project; (7) Examples of ongoing demonstration projects focusing on GH2 subsurface storage in depleted fields and aquifers: EU-level Project Hyuspre (timeline 2020 – 2023) and Project HyStorPor in the UK (timeline 2019-2023); (8) For comparison, in 2019, the Storage to Demand ratio (storage capacity as a percentage of annual demand) for natural gas in the EU was equal to about 20-22% (EnTEC, 2022); (9) Gas Infrastructure Europe, 2021 ; (10) EnTEC, 2022; (11) It must be considered that since renewable hydrogen demand is expected to be relatively stable throughout the year (not much of it is expected to be consumed in residential heating applications, at least until the 2040s), the future storage-to-demand ratio applied in the hydrogen sector is likely to be lower than the current storage-to-demand ratio applied in the natural gas market (where the need for storage originates from the temporal difference between a relatively constant supply and a highly seasonal demand); (12) Caglayan, et al, 2020.

R&I challenges and associated recommendations for the storage of hydrogen in salt caverns

Description of the R&I challenge: Worldwide, 4 storage facilities for pure hydrogen in salt caverns are already operational (for back-up supply to petrochemical complexes, static storage), and practical experience with these sites has shown that hydrogen can be safely stored in this way for long periods of time. However, to provide flexibility to a coupled electricity-hydrogen energy system, injection and withdrawal are expected to occur much more frequently and cyclically, and at higher volumetric rates than is currently the case[1]. Important challenges remain to be addressed in this context, in particular in relation to a) selection of H_2-compatible materials and components, integrity of wellbore materials and interfaces, b) de-risking microbial activity and geochemical reactions in caverns, c) the geomechanically response of the subsurface to fast-cycle operation, d) up-scaling of technologies for compression (pre-injection) and cleaning (post-withdrawal of H_2, e) adapting standards and regulations for natural gas to hydrogen, and f) the techno-economic feasibility of offshore storage vs. onshore.

Objective: **Upscaling to (pre-commercial) demonstration-scale, integration into the H_2 transport and energy system,**

- **Target for 2030:** > 3000 tons of H_2 storage per cavern (commercial-scale, TRL 9)
- **Cost target in 2030**: Capital cost < 30 Euros/kg of H2[2]
- **Research Timeline**: 2023-2028

Where are we today: Successful demonstration of hydrogen storage on a small scale, i.e., small volumes of H2, and small salt caverns[3]

Technical R&I aspects: The main knowledge gaps relate to the selection of H_2-compliant materials and components in a wet, salt-saturated environment, impact of fast-cycle operation on integrity of wells and interfaces, risks of loss and/or conversion of hydrogen due to microbial activity and/or geochemical reactions in salt caverns, surface facility design and engineering, and the geomechanical response of the caverns and surrounding subsurface to fast-cycle operation.

R&I projects should focus on:

> Selection guidelines for H_2-compliant materials and components that ensure the long-term integrity and durability of wells during storage lifetime.

> Effects of microbial activity and geochemical reactions on recoverablity and purity of the hydrogen, and measures to mitigite the effects.

> Quantifying the geomechanical response of the caverns and surrounding subsurface to fast-cycle operation.

> Large-scale demonstration of H_2-storage (and integration in the system) that is progressing the state of art. (e.g., in terms of capacity and rates).

***Project example :** Hystock (near port of Eemshaven)*

Recommendation: **The EU and/or Member States should consider to allocate direct public funding** to innovative public-industry R&I projects aiming at advancing the technological maturity of seasonal hydrogen storage in **salt caverns in vicinity of ports.**

Notes: (*) Data taken from Funding & tenders (europa.eu).
Sources: (1) TNO, 2020; (2) Strategic Research and Innovation Agenda (page 158); (3) HyStock.

R&I challenges and associated recommendations for the storage of hydrogen in reservoirs (depleted fields and aquifers)

Description of the R&I challenge: Gas fields are larger in volume than salt caverns and are more geographically widespread. While there is decades of experience with storage of natural gas in reservoirs, no site exists where pure hydrogen is stored, and its technical and economic feasibility must be proven. Important challenges that remain to be addressed relate to a) conversion and contamination of H_2, b) storage integrity (long-term leak-tightness of gas reservoirs for H_2?), c) storage performance, d) selection of H_2-compatible materials and components, e) integrity of wellbore materials and interfaces, f) surface facility design and upscaling, g) economics and system integration and h) HSE de-risking.

Objective: **Demonstrate feasibility of pure H_2 storage in porous reservoirs at reduced scale (pilot-scale)**

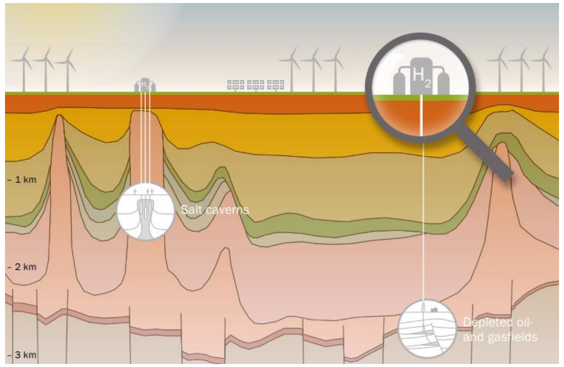
- **Target for 2030**: 1 kt of H_2 storage (pre-commercial, TRL 7-8)
- **Cost target in 2030**: Proof of concept capital cost < 5 euros/kg of H_2[1]
- **Research Timeline**: 2023-2028

Where are we today: Two CH-JU funded R&D (RIA) projects (HyUSPRe, Hystories) are assessing the techno-economic feasibility and potential of large-scale storage of (pure) hydrogen in porous reservoirs (depleted gas fields, aquifers or depleted fields in Europe. Successful demonstrations of storing blends of H_2 and natural gas in Austria and Argentina.

Technical R&I aspects : Recent demonstration projects in Argentina and Austria with injection of up to 10% of hydrogen in a mix with natural gas into a depleted gas field have shown that hydrogen can be safely stored without adverse effects to installations and the environment[2].

R&I projects should focus on:

- Assessing the impact of geo- and biochemical reactions of H_2 with rocks, fluids and micro-organisms in reservoirs, to better understand the potential (technical, environmental, economic) risks and how to mitigate.
- Storage integrity, i.e., proving that H_2 can be safely stored in reservoirs without leakage/loss
- Understanding H_2 flow and mixing behavior with other fluids in reservoirs to quantify performance and recoverability
- Selection guidelines for H_2-compliant materials and components that ensure the long-term integrity and durability of wells during storage lifetime
- Design, upscaling and economic optimization of purification installations of the withdrawn H_2, and waste stream processing
- HSE risk management, i.e., assess risks, develop mitigations, and develop/apply site monitoring techniques for measuring real-time env. impact.



Schematic illustration of technology concepts for underground hydrogen storage[3]

Recommendation: The EU and/or Member States should consider to allocate direct public funding to innovative public-industry R&I projects aiming at advancing the technological maturity of seasonal hydrogen storage in **porous reservoirs in vicinity of ports**

Notes: (*) In the lighthouse project "Underground Sun Storage 2030" (USS 2030), the safe, seasonal and large-scale storage of renewable energy in the form of hydrogen in underground gas reservoirs is being developed. **Sources**: (1) Strategic Research and Innovation Agenda (page 158); (2) TNO, 2020. Large-Scale Energy Storage in Salt Caverns and Depleted Fields (LSES); (3) HyUSPRe.

Safety challenges and associated recommendations for the large-scale development of hydrogen underground storage solutions

Description of the safety challenge: Positive public support for the large-scale underground storage of hydrogen in a not yet self-regulating market and on a geological/technical level the behavior of hydrogen in the subsurface and potential subsidence effects.

Objective: **Development of a European Directive on the geological storage of hydrogen**

Where are we today: The European Directive 2009/31 on the geological storage of carbon dioxide, in force since 2009, and the Directive 2009/73 for natural gas provide a starting point for a similar directive on hydrogen. The Commission delegated regulation 2021/2139 and 2020/852 provide incentives for (not exclusively) underground hydrogen storage[1;2]. Multiple demonstration projects are/were executed in among others Germany, Austria, France and the Netherlands (HyStock)[3]. All on small scale and as a precursor for medium and subsequent large-scale salt caverns and gas storage facilities. Salt caverns are closer to technical realization and implementation and are more predictable in terms of behavior of hydrogen compared to empty gas fields (porous rock).

Safety projects should focus on:

- Migration (diffusion/permeation) of hydrogen to the subsurface is a function of the materials present in the subsurface layer. The rate of migration of hydrogen needs to be determined to select the most suitable locations for storage of hydrogen and the effect subsidence has on this.
- The interaction of water with hydrogen as a function of the other gases present in the cavern/empty gas field determine the migration rate of hydrogen. These gas-water effects need to be understood to determine the most effective sealing method of hydrogen in the rock materials.
- With hydrogen being smaller and a more diffusive species, a better understanding of the progressive growth of cracks and defects in materials (like pipelines) is needed, especially in relation to the frequent pressure variations.
- The microbiological impact in caverns/empty gas fields needs to be better understood, as this may lead to the formation of unwanted products, like the toxic hydrogen sulfide which also affects wellbore materials.

Recommendations:

- The EU should **involve the Gas Infrastructure Europe association**, representing the operators of gas infrastructure across Europe, in developing protocols and guidelines for the underground storage of hydrogen.
- The EU should **support the development of certification protocols of wellbores to be used for hydrogen storage in existing gas storage facilities**.

Sources: (1) Regulation (EU) 2021/2139; (2) Regulation (EU) 2020/852; (3) HyStock

Non-technical challenges associated with the development of **hydrogen underground storage solutions**

Non-technical challenges hindering the **development of large-scale hydrogen storage in underground geological formations:**

1. **Lack of clear market perception for the need for large-scale cyclical and seasonal hydrogen storage**, at least until hydrogen becomes an internationally traded commodity in large quantities (millions of tons per year)[1].
2. **Lack of an EU regulatory framework for hydrogen storage in underground geological formations** addressing investments certainty, cost-reflectivity, distortion of competition of the internal energy market due to different regulatory regimes, etc. For instance, underground hydrogen storage may require **regulations to guarantee non-discriminatory third-party access** (particularly in Member States with low underground hydrogen storage potential and lower hydrogen storage needs), given limited availability of geological sites in some regions and the attractive economic competitiveness compared to other solutions[2]. Overall, **different regulatory approaches for salt caverns and other underground storage will be warranted in the various Member States**.
3. **Lack of sufficient recognition for storage needs and benefits** (e.g., in ensuring system security) **in energy sector planning**, leading to the establishment of market design and network tariffs that do not reward the value of hydrogen storage[3].
4. **Lack of a clear EU and national regulatory framework for the conversion of currently regulated underground gas storage to hydrogen storage**[4].
5. **High CAPEX investments and very long lead times** in the planning and development of underground storage options[5].
6. **Lack of investment in R&I activities** that aims at demonstrating the technico-economic feasibility of hydrogen storage in underground geological formations.

Notes: (1) A development of the hydrogen market based on long-term bilateral agreements may initially restrict the liquidity of organized markets, therefore limiting the need for large-scale cyclical and seasonal hydrogen storage (EnTEC, 2022). Also, it can be assumed that most electrolysers would run in a more baseload mode of operation to eliminate the need of large-scale cyclical and seasonal storage (Gas Infrastructure Europe, 2021); (2) In Member States with lower underground storage potential, the potential for market concentration is higher and therefore more regulatory framework for Third Party Access might be needed (EnTEC, 2022); (3) The storage contributions to security of supply may not be properly valued due to an inability of market players to adequately estimate the probability of rare supply disruption or infrastructure outage events, or due to the absence of incentives for them to do so (EnTEC, 2022); (4) The most relevant EU legislation for this case is the Offshore Safety Directive (DIRECTIVE 2013/30/EU), which establishes rules for decommissioning of natural gas and oil offshore infrastructure. Although it concerns mainly the environmental impacts of decommissioning, it also contains provisions on identifying the parties responsible for the decommissioning and defining their liability; (5) From a technical point of view, repurposing hydrogen storages can take anywhere from 1 to 7 years, and developing new storage assets can take from 3 to 10 years.

Recommendations for addressing non-technical challenges related to the development of **hydrogen underground storage solutions** (1/2)

Responsible authority(ies)**: Port authorities and other port stakeholders**

1

In major ports along the North Sea coast (France, Belgium, the Netherlands, Germany, and Denmark) that are likely to first host hydrogen or hydrogen carrier import terminals, **port authorities should work with relevant port and non-port stakeholders to assess the long-term societal relevance and the techno-economic rationale** (from the perspective of energy system security) **of developing seasonal hydrogen storage solutions in offshore subsurface geological formations located in the vicinity of the port area** (e.g., within 50 km). To this end, port authorities should support the development of feasibility studies and pilot projects to determine if and/or when hydrogen storage in offshore subsurface geological formations will be needed from a demand perspective (i.e., to determine how much of the imported hydrogen will be used directly or stored in tanks at import terminals and how much of the imported hydrogen will need to be stored for seasonal energy system flexibility), as well as the technical and economic implications of the development of this activity for the port area (e.g. on land-based infrastructure, land-use planning, gas network capacity, etc.).

2

In particular, given the high CAPEX investments and the very long lead times for planning and developing underground (offshore) storage solutions, **port authorities** in the European north-western (i.e., the Netherlands, Germany, Denmark and Poland) coastal areas **should already be preparing for the eventuality that the development of hydrogen storage solutions in offshore underground geological formations located near port areas turns out to be positive.** For instance, port authorities should seek to understand how they can best contribute to the following considerations (non-exhaustive):

- Who is the stakeholder responsible for addressing supply variability (to find out who has the primary responsibility for planning storage investments)?
- How can individual projects develop and ensure a sustainable business case?
- How best to facilitate the transport of GH2 to and from large-scale cyclical and seasonal offshore storage?
- How best to facilitate the negotiation of the long-term agreements needed to secure sufficient capacity and investment security (investors in underground hydrogen storage solutions will not be able to rely initially on short-term market revenues and will face large upfront investments)?
- Which EU and national R&I funding programs could be leveraged for these projects?

Recommendations for addressing non-technical challenges related to the development of **hydrogen underground storage solutions** (1/2)

Responsible authority(ies): **The European Union (EU) and Member States**

1 **The EU should develop and implement a clear and flexible regulatory framework for developing hydrogen storage markets that provides the necessary certainty for investments**. In particular, regulations to guarantee non-discriminatory third-party access should be developed in order to enable hydrogen storage operators to offer storage services to Member States with limited availability of suitable underground storage sites through long-term contracts.

2 Given that leaving the responsibility of regulating underground gas storage infrastructure repurposing to Member States will likely lead to uneven market conditions for potential storage operators, **the EU should define a clear EU regulatory framework for enabling the conversion of currently regulated underground gas storage to hydrogen storage for when this operation is beneficial from societal perspective**.

3 **They EU should disseminate best practices and providing guidance on permitting procedures to Member States** for the development of underground (offshore) hydrogen storage solutions (in the vicinity of ports).

4 **The EU should require Member States to consider hydrogen systems and the benefits of hydrogen storage in energy sector planning** at the national level. For instance, this could be done by integrating national hydrogen demand and supply forecasted in the NECPs in the plans of network operators (electricity and gas) for network development (NDP).

5 **EU and national energy policies and regulations** (including market designs and network tariffs) **should better reflect the system flexibility value of storage** (e.g., increasing temporal and locational granularity of the system planning could support better valuations).

Glossary

Glossary of key terms and concepts (1/3)

Term	Full description
Seaport	A port located on a sea or ocean coastline.
Inland port	A port not located on a sea or ocean coastline.
Port authority	A public or a private entity that, whether or not in conjunction with other activities, under national law or regulation is empowered to carry out the administration, development, management, operation of the port land and infrastructure (occasionally) and the coordination and control of port operation activities. The conventional roles of a port authority are those of a landlord, a regulator, and an operator of the port.
Port-related stakeholders	Companies, institutions, groups or individuals that have power and/or interest in port areas and related activities. In the frame of this study, it includes (non-exhaustive): regulatory authorities, sea tankers operators, terminal operators, renewable (wind and solar) electricity producers, technology innovators and manufacturers, hydrogen producers, storage infrastructure providers, electricity and gas infrastructure providers, bunkering infrastructure providers, shipping companies, ship owners, industrial hydrogen consumers, heavy-duty road transport companies, local communities, local cities, financial investors, etc.
Port area	Land and sea area located in the immediate vicinity of ports and accommodating activities and/or infrastructure (e.g., industrial, transport, storage, logistics) directly or indirectly related to port operations.
EU Member State	Means a country which, for the time being, is a member state of the European Union.
The European Union	Means the institutions, agencies and decision-making bodies which govern the administration of the EU, provide policy guidance and initiate and coordinate the development of EU legislation.
‘Europe’ or ‘European countries’	Include the 27 Member States of European Union (EU27), United Kingdom, Norway and Switzerland.
GH2	Refers to hydrogen in its gaseous state. In the frame of this study, GH2 often means compressed gaseous hydrogen, which is gaseous hydrogen kept under pressure either for use as a fuel gas or for storage (i.e., in tanks) and transportation (e.g., by pipeline, tube trailer, etc.).
LH2	Refers to hydrogen in its liquid state. GH2 Gaseous hydrogen is liquefied by cooling it to below −253°C. Once hydrogen is liquefied it can be stored at a liquefaction plant in insulated tanks. LH2 has a higher density and fewer potential risks in terms of storage pressure compared with the compressed gas.
Grey hydrogen	Fossil-based hydrogen produced through the reforming of natural gas.
Blue hydrogen	Fossil-based hydrogen produced through the reforming of natural gas in plants equipped with CO2 capture units and subsequent CO2 storage.
Green hydrogen	Also called “renewable hydrogen”, green hydrogen is obtained via electrolysis using renewable-based electricity (e.g., onshore and offshore wind, solar PV) to split water into hydrogen and oxygen.
Hydrogen carriers	Hydrogen-rich liquid or solid phase materials from which hydrogen can be liberated on demand. In the frame of this study, it mainly includes ammonia, and LOHC, but also methanol and other e-fuels.

Glossary of key terms and concepts (2/3)

Term	Full description
Ammonia	Ammonia is an inorganic compound of nitrogen and hydrogen with the formula NH3. In addition to being used as a raw material for fertilizer, ammonia can also be used to store and transport hydrogen, or directly as a fuel.
LOHC	Liquid organic hydrogen carriers (LOHC) are organic compounds that can absorb and release hydrogen through chemical reactions. LOHC technology eliminates the need for compression and make the transport of hydrogen safer, more practical and more cost-efficient (existing conventional fuel networks can be used).
Methanol	Methanol production processes are based on a feed consisting of predominately hydrogen, carbon monoxide and CO2. In addition to being used as an industrial feedstock for producing a wide range of chemicals, methanol can also be used to store and transport hydrogen, or directly as a fuel.
Fuel cells	A fuel cell uses the chemical energy of hydrogen (or other fuels) to cleanly and efficiently produce electricity. If hydrogen is the fuel, the only products are electricity, water, and heat. Today, fuel cells are used for primary and backup power for commercial, industrial and residential buildings and in remote or inaccessible areas. They are also used to power fuel cell vehicles, including forklifts, automobiles, buses, trains, boats, motorcycles, and submarines.
Governance of hydrogen and hydrogen carrier-related activities and infrastructure in port areas	Institutional and organisational structure defining and governing the development of hydrogen and hydrogen carrier-related activities and initiatives in each port ecosystem and coastal area.
Import terminals of hydrogen and hydrogen carriers	Providing terminalling infrastructure in ports for the safe offloading and handling of LH2 and hydrogen carriers (ammonia, methanol and LOHC), either at converted LNG terminals or at newly constructed dedicated LH2 and hydrogen carrier terminals.
Bunkering of hydrogen and hydrogen derivatives	Bunkering of hydrogen/hydrogen carriers (i.e., ammonia, methanol) for use as fuel by ships, including *shore-to-ship* (fuel bunkered directly from a storage tank or pipelines), *ship-to-ship* (fuel bunkered from cargo tanks of a refueling vessel)[1] and *truck-to-ship* (fuel bunkered from a truck connected to the ship on the quayside)[2], but also floating ammonia bunkering systems and swappable compressed hydrogen (GH2) containers.
Use of hydrogen and hydrogen-based fuels in the maritime sector	Use of hydrogen (compressed or liquid form) or hydrogen-based fuels (ammonia, methanol, e-fuels) as a fuel in maritime activities, both in deep-sea and short-sea applications, as well as in inland navigation activities.
Use of hydrogen and hydrogen carriers in cold ironing	Use of hydrogen or hydrogen carrier as a fuel in fuel-cell onshore power supply (OPS) systems (stationary or mobile) or dual-fuel hydrogen internal combustion engines, when direct electrification is not the most cost-efficient decarbonization pathway
Use of hydrogen and hydrogen carriers in land-base cargo handling and terminal equipment	Use of hydrogen or hydrogen carrier as a fuel in land-base cargo handling and terminal equipment, such as straddle carrier, terminal tractors, forklifts, rubber-tired gantry cranes and mobile harbor cranes, when direct electrification is not the most cost-efficient decarbonization pathway.

Glossary of key terms and concepts (3/3)

Term	Full description
Renewable hydrogen production in ports areas	Production of renewable hydrogen from water electrolysis and renewable-based electricity (offshore wind, onshore wind and solar PV) in (large-scale) electrolysers facilities located in the vicinity of ports (either onshore or offshore next to wind farms).
Surface hydrogen and derivatives storage solutions	Above-ground storage of hydrogen and hydrogen carriers in stationary or mobile tanks at import terminals, either in compressed (compressed hydrogen) or liquid (LH_2, ammonia, LOHCs, methanol) form, for short- to medium-term (hours or days/months) storage prior to transport to locations with high demand for green hydrogen and low local production possibilities.
Conversion of imported hydrogen carriers into hydrogen	Conversion of imported hydrogen carriers (ammonia or LOHC) into hydrogen (in its gaseous form) through the construction of industrial-scale ammonia cracking and LOHC dehydrogenation facilities in European import terminals.
Multimodal land-based hydrogen refueling stations (HRSs)	Fueling/bunkering of (compressed) hydrogen for use as a fuel by inland shipping, short-distance maritime operations, port equipment machineries (cargo handling and terminal equipment) and road trucks at a land-based hydrogen refueling station comprising the following specific technical components: adequately sized storage facilities for hydrogen (to bring the hydrogen to the desired gas pressure level), a precooling system, and dispensers for delivering the fuel.
Transport of hydrogen and derivatives from ports to end-users	Inland transportation of hydrogen (in a compressed or liquid form) and hydrogen carriers in truck trailers, trains and inland ships (barges) from port areas to various end users in the hinterland.
Deep sea transport of hydrogen and hydrogen carriers via tankers	Seaborne commercial transportation (in tankers) of hydrogen in the form of GH2, LH2), ammonia , LOHC or methanol.
Storage of GH2 in underground geological formations	Storage of GH2 in underground geological formations (i.e., salt caverns, aquifers and depleted oil and gas fields) for large-scale cyclical and seasonal storage.

List of abbreviations

Acronym	Full description
AFIR	Alternative Fuel Infrastructure Regulation
ATEX	European Directives for controlling explosive atmospheres
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CCNR	Commission centrale pour la navigation du Rhin
CEF	Connecting Europe Facility
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CESNI	European Committee for Drawing up Standards in the Field of Inland Navigation
CO_2	Carbon dioxide
EFIP	European Federation of Inland Ports
ESPO	European Seaports Organization
ETD	Energy Taxation Directive
ETS	European Emission Trading System
EU	European Union
GHG	Greenhouse Gases

Acronym	Full description
GH2	Gaseous Hydrogen
GJ	Gigajoules
GW	Gigawatt
HDVs	Heavy Duty Vehicles
HRS	Hydrogen Refueling Stations
H2	Hydrogen
IGC Code	International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels
IMO	International Maritime Organization
IPCEI	Important Projects of Common European Interest
ISM Code	The International Safety Management (ISM) Code
ISO	International Standards Organization
kg	Kilogram
LH2	Liquefied Hydrogen
LOHC	Liquid Organic Hydrogen Carriers
LNG	Liquefied Natural Gas

Acronym	Full description
MARPOL	International Convention for the Prevention of Pollution from Ships
Mt	Million tons
NECPs	National Energy and Climate Plans
OPEX	Operational Expenditure
OPS	Onshore Power Supply
PEM	Polymer electrolyte membrane
PV	Photovoltaic
RCF	Recycled Carbon Fuel
RED	Renewable Energy Directive
RES	Renewable Energy Sources
RFNBOs	Renewable Fuels of Non-Biological Origins
R&I	Research and Innovation
TEN-E	Trans European Network for Energy
TEN-T	Trans European Network for Transport
TRL	Technology Readiness Level
ZEWT	Zero-Emission Waterborne Transport

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Note: (1) The contribution of TNO to this study is limited to expert analysis of priority areas for R&I and safety projects and associated recommendations for each of the types of hydrogen and hydrogen carrier related activities and infrastructure in the scope of this report.

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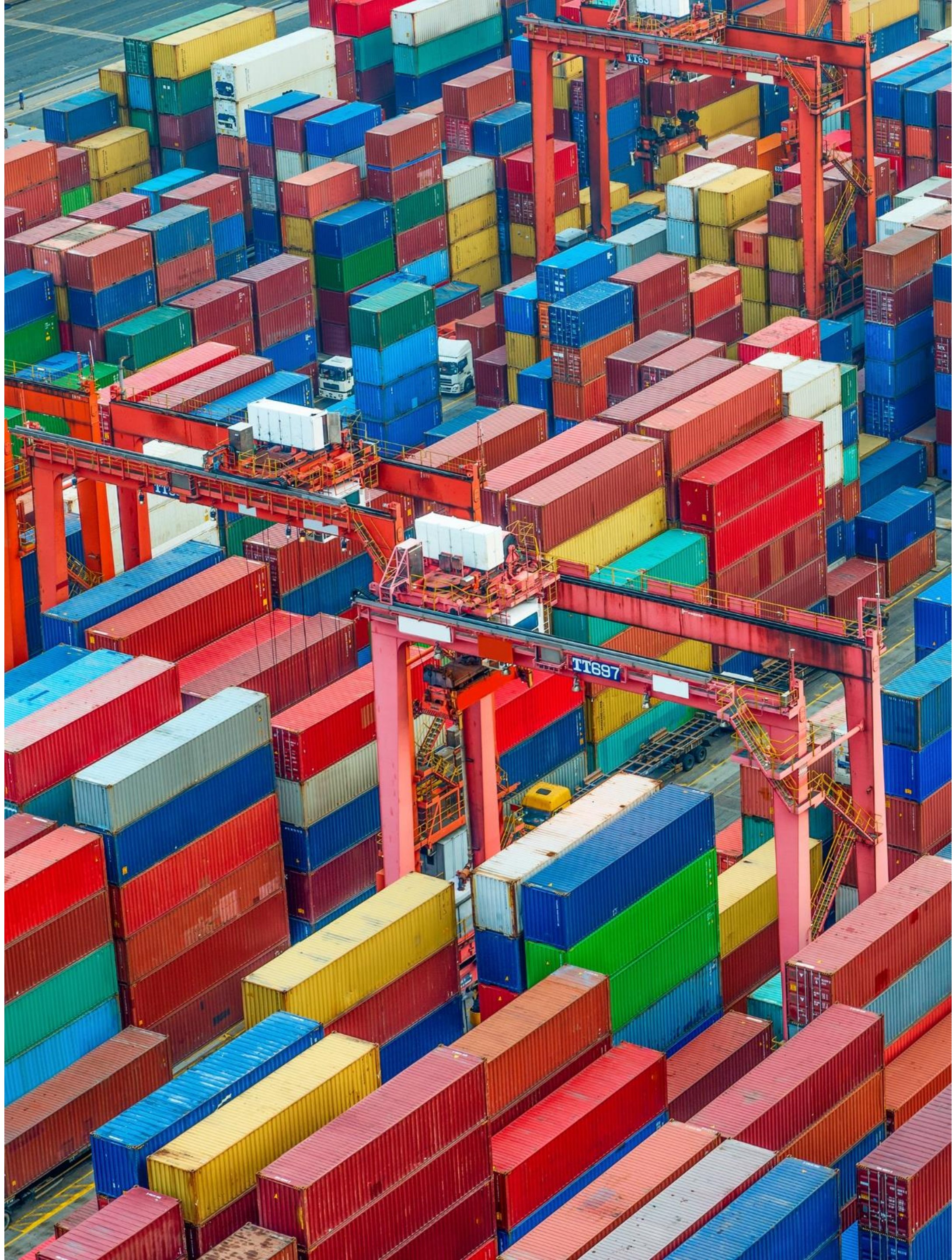

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