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TransH2

TransH2

D1.3.4 Joint cross border strategy

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1. Introduction

1.1. Project Overview

The TRANSITION TO HYDROGEN FUELLED CROSS-BORDER SEA-MOBILITY – TRANSH2 project focuses on enhancing the sustainability of cross-border sea mobility in the Adriatic region. It aims to modernize maritime connections by implementing low-carbon transport solutions, specifically zero-emission fuels like green hydrogen. By demonstrating the feasibility and benefits of these solutions, the project seeks to promote their adoption among port authorities, transport operators, and other stakeholders in the area.

The ultimate goal is to contribute to the European Green Deal objectives by significantly reducing emissions from the maritime sector. To achieve this, the project will focus on developing innovative hydrogen-fueled vessels and infrastructure, ensuring a full hydrogen supply chain for maritime transport in Italy and Croatia.

The primary goal of TRANSH2 is to demonstrate the feasibility of hydrogen as a fuel for maritime transport, showcasing its practical applications to port authorities, transport operators, and stakeholders across the program area. By integrating zero-emission hydrogen technology into maritime mobility, the project directly supports the European Green Deal’s goal to reduce maritime sector emissions by 90% by 2050. It also aligns with the EU’s mission to “Restore our Ocean and Waters” by contributing to zero pollution and greenhouse gas emission reductions in EU waters.

TRANSH2 emphasizes the critical role of research and innovation in establishing a complete hydrogen supply chain for maritime transport. The project aims to develop hydrogen-powered vessels and build the necessary refueling infrastructure in ports, targeting the European Sustainable and Smart Mobility Strategy's 2030 milestone for market-ready zero-emission vessels.

TRANSH2 also highlights the economic potential of transitioning to hydrogen fuel, leveraging its ability to stimulate innovation, create jobs, and diversify the regional economy. This transformation can not only reduce environmental impacts but also enhance the safety, cleanliness, and efficiency of transport systems.

However, the deployment of hydrogen technology in maritime transport presents significant challenges, including high investment costs, the need for regulatory and safety frameworks, and the development of port infrastructure. TRANSH2 recognizes the necessity of collaboration between public and private stakeholders to overcome these barriers and drive the successful adoption of hydrogen solutions.

By fostering cross-border cooperation and knowledge exchange, TRANSH2 aims to position the Adriatic region as a leader in sustainable maritime transport, setting an example for other regions in Europe and beyond.

1.2. Background

The maritime industry is at a crossroads, facing significant challenges posed by stringent environmental regulations, globalization uncertainties, geopolitical dynamics, digitalization, and cyber risks. These complexities demand swift and innovative responses, particularly in the pursuit of decarbonization. Shipping stakeholders are urgently exploring strategies to improve propulsion efficiencies and adopt cleaner fuel options to meet environmental and regulatory demands.

Among the most pressing threats to the planet is the rise in global temperatures, primarily driven by anthropogenic greenhouse gas (GHG) emissions. The shipping industry contributes approximately 3% of global CO_2 emissions, making it a critical sector for action to achieve a sustainable future.

In line with global climate initiatives, the International Maritime Organization (IMO) adopted the Initial GHG Reduction Strategy in 2018 (Resolution MEPC.304(72)), committing to reduce GHG emissions by at least 50% by 2050 compared to 2008 levels. This ambition was further strengthened during MEPC 80 in 2023, with an increased commitment to achieve net-zero GHG emissions by or around 2050. These targets have set the stage for the adoption of zero-carbon and low-carbon fuels within the maritime sector.

However, the transition presents challenges, particularly as commercial ships often have operational lifespans exceeding 20 years, leading to investment hesitancy amidst regulatory and technological uncertainties. The need for decisive action is underscored by mounting pressure from European Union regulations, which demand an accelerated response to decarbonization.

Hydrogen fuel has emerged as a transformative solution, offering a clean, renewable energy source with the potential to revolutionize maritime transport. As a versatile energy carrier, hydrogen can be used directly as a zero-emission fuel or as a feedstock for the production of alternative fuels and chemicals. Increasingly, shipbuilders, operators, and port authorities are exploring hydrogen as an environmentally sustainable alternative to fossil fuels.

This strategy focuses on hydrogen’s role in greening maritime transport within the Adriatic region, particularly through cross-border collaboration between Croatia and Italy. It highlights the practical application of hydrogen-powered solutions, supporting regional objectives to decarbonize maritime transport while fostering innovation, sustainability, and economic growth.

1.3. Objectives

The joint strategy aims to position the Adriatic region as a leader in the transition to sustainable maritime transport through the adoption of hydrogen as a clean energy source. It leverages the expertise of the H2 maritime transport collaboration network and external experts to establish a comprehensive framework for greening maritime transport routes. Rooted in environmental responsibility, cross-border cooperation, and economic innovation, the following objectives define the strategy's purpose:

- **Promote Hydrogen as a Sustainable Energy Source**

Hydrogen is central to this strategy as a zero-emission fuel with the potential to address the maritime industry's environmental challenges. The strategy aims to integrate hydrogen into maritime transport systems by raising awareness among key stakeholders—such as port authorities, shipping companies, and policymakers—about its environmental and economic benefits. In addition, it focuses on addressing technological, logistical, and operational barriers to enable the widespread adoption of hydrogen as a viable alternative to fossil fuels. By supporting the European Green Deal's goal of reducing maritime emissions by 90% by 2050, the strategy seeks to position the Adriatic region as a model for green maritime practices.

- **Develop Cross-Border Collaboration Frameworks**

The successful implementation of hydrogen technologies in maritime transport relies on robust cross-border cooperation. This strategy highlights the importance of harmonizing policies and regulations between Croatian and Italian regions to streamline the adoption of hydrogen solutions. It also focuses on establishing partnerships between public authorities, private enterprises, and research institutions to foster innovation and accelerate the deployment of hydrogen technologies. Additionally, the strategy aims to leverage joint investments in hydrogen infrastructure, including production, storage, and refueling facilities, to ensure maximum impact and efficiency in advancing sustainable maritime transport.

- **Enhance Energy Efficiency in Maritime Transport**

Improving energy efficiency in maritime operations is a cornerstone of this strategy. It emphasizes integrating hydrogen-powered vessels and renewable energy technologies to optimize energy performance, reduce fuel consumption, and minimize emissions. The strategy also focuses on modernizing port infrastructure to include energy-efficient systems, such as cold ironing and renewable energy-powered charging stations, to facilitate the adoption of hydrogen as a maritime fuel. Furthermore, it encourages the deployment of hydrogen-powered ferries and cargo vessels, ensuring both sustainability and operational efficiency across cross-border routes.

- **Stimulate Regional Economies Through Green Innovation**

The adoption of hydrogen in maritime transport offers a unique opportunity for economic growth and innovation. This strategy aims to drive the development of green technology sectors by creating new jobs in hydrogen production, shipbuilding, and infrastructure development. It also seeks to support local industries, including shipyards and renewable energy providers, in integrating hydrogen into their operations and contributing to the hydrogen value chain. Additionally, the strategy focuses on attracting investments and enhancing the Adriatic region's competitiveness as a global leader in sustainable maritime transport, fostering long-term economic resilience and diversification.

2. Regional Analysis

The following is a brief analysis of key regional segments included in the project, providing insights relevant to the broader application of this strategy.

2.1. Primorje-Gorski Kotar County

Primorje-Gorski Kotar County, located in the northern Adriatic Sea, serves as a vital maritime and economic corridor connecting Central Europe to the Mediterranean. Its diverse geography, encompassing coastal areas, islands, and hinterlands, makes it a hub for passenger, cargo, and industrial maritime activities. At the center of this network lies the Port of Rijeka, Croatia's largest seaport, which handles significant cargo and passenger traffic and plays a critical role in international maritime routes. With its modernized infrastructure, the port is well-suited for integrating hydrogen refueling stations and renewable energy systems, aligning with the goals of sustainable maritime transport.

In addition to the Port of Rijeka, smaller ports such as Cres, Krk, Rab, and Mali Lošinj are key to maintaining inter-island connectivity, supporting tourism, and driving local economies. Ports like Opatija and Crikvenica play an equally important role in short-distance passenger transport and nautical tourism. Furthermore, renowned marinas, including Marina Punat and ACI Marina Opatija, cater to the growing nautical tourism sector and present opportunities for implementing hydrogen fueling solutions for recreational vessels.

The county's maritime transport infrastructure is extensive and advanced, providing a solid foundation for the adoption of hydrogen technologies. The existing ferry network, managed by operators such as Jadrolinija, connects the mainland to major islands, including Krk, Cres, Lošinj, and Rab. These high-traffic and frequent ferry routes are ideal pilot platforms for deploying hydrogen-powered ferries. The Port of Rijeka’s modernized terminals and logistics hubs already support large-scale maritime traffic, while ongoing upgrades in smaller ports, including digital systems and renewable energy integration, further align with hydrogen transition objectives.

Primorje-Gorski Kotar County is actively preparing for hydrogen-ready infrastructure. Rijeka Port is positioned to become the central hub for hydrogen refueling, leveraging its advanced logistics capabilities and international significance. Smaller ports, particularly on Krk Island, are also primed to provide localized hydrogen solutions, especially for high-frequency inter-island routes. Planned developments include dockside facilities equipped with renewable energy-powered charging stations and hydrogen fueling points, paving the way for green maritime initiatives.

The county’s renewable energy potential further enhances its ability to produce green hydrogen. Projects such as wind farms and solar initiatives, particularly on Krk Island, provide a robust foundation for clean hydrogen production. The industrial sector, including the Rijeka Refinery and local shipyards, is poised to play a pivotal role in developing hydrogen production and distribution infrastructure. Shipyards in Rijeka and Kraljevica, in particular, have the capacity to retrofit existing vessels and construct new hydrogen-powered ships, fostering maritime innovation and supporting the transition to cleaner technologies.

Investments in hydrogen technologies present significant opportunities for economic diversification. These investments can reduce reliance on traditional industries, stimulate innovation, and create jobs in green technology sectors. The county's development strategies already emphasize renewable energy, sustainable tourism, and eco-friendly transport, making the adoption of hydrogen a natural extension of its broader economic and environmental goals.

While challenges remain, including high infrastructure costs, limited local expertise in hydrogen technologies, and seasonality in maritime activity, the county is well-positioned to address these issues. Training programs and partnerships can help bridge the expertise gap, while EU funding opportunities through initiatives like Horizon Europe, Interreg, and the European Green Deal can support the development of hydrogen infrastructure.

The county’s high-traffic ferry routes between Rijeka and islands like Krk and Cres offer ideal conditions for pilot projects using hydrogen-powered vessels. With its strategic location, advanced maritime infrastructure, and commitment to sustainability, Primorje-Gorski Kotar County is well-placed to establish itself as a regional leader in sustainable maritime transport. This initiative not only enhances environmental protection but also fosters long-term economic growth and innovation, solidifying the county’s reputation as a pioneer in green maritime solutions.

2.2. Šibenik-Knin County

Šibenik-Knin County, renowned for its tourism-driven maritime activities, offers significant potential for adopting hydrogen-powered solutions to reduce its environmental footprint. With its strategic coastal position and economic dependence on maritime transport, the county is ideally placed to implement hydrogen as a fuel for leisure and commercial vessels, promoting sustainable and green maritime operations.

Geographically, Šibenik-Knin County is situated in central Dalmatia along the Adriatic Sea, characterized by its rugged coastline and numerous islands. Its central location on major maritime routes positions it as a vital connector between northern and southern Croatia, as well as neighboring countries. The Port of Šibenik serves as the county’s primary maritime hub, with facilities for both cargo and passenger traffic. Its infrastructure makes it an ideal candidate for hydrogen integration, and its role in hosting international cruise ships underscores the need for sustainable technologies to reduce emissions. Complementing the main port, smaller ports in Vodice, Primošten, and Rogoznica are critical for tourism and connecting mainland towns to nearby islands. Ports like Murter and Zlarin also play a vital role in supporting local communities and eco-tourism, creating opportunities for integrating hydrogen-powered ferries.

The county’s dense marina network further enhances its potential for hydrogen adoption. Marinas such as Marina Mandalina and Marina Frapa in Rogoznica are leaders in nautical tourism and present viable hubs for hydrogen fueling stations tailored to recreational vessels. This network supports the county’s position as a key player in the transition to sustainable maritime solutions.

The existing maritime transport infrastructure provides a strong foundation for hydrogen integration. A well-developed ferry network connects the mainland to key islands such as Žirje, Kaprije, and Prvić. Managed by operators like Jadrolinija, these year-round services are essential for regional connectivity and economic activity, making them prime candidates for pilot projects featuring hydrogen-powered vessels. The Port of Šibenik's modern infrastructure can accommodate upgrades for hydrogen refueling and renewable energy integration, while ongoing initiatives in modernizing local ports and marinas further align with the county's hydrogen transition goals.

Šibenik-Knin County is already preparing for hydrogen-ready infrastructure. The Port of Šibenik is strategically positioned to host hydrogen fueling stations for both domestic and international maritime traffic. Smaller ports and marinas are also well-suited to support hydrogen-powered ferries and eco-tourism vessels. Future developments include plans to integrate renewable energy-powered charging stations and hydrogen production facilities at key ports, enhancing the county's sustainability efforts.

The county's renewable energy potential further strengthens its hydrogen readiness. Wind farms near Knin and solar projects in inland areas provide a reliable foundation for green hydrogen production. Local shipyards, such as NCP Repair Shipyard in Šibenik, are well-equipped to retrofit vessels and develop hydrogen-powered maritime technologies, driving innovation in the region. Investments in hydrogen infrastructure also offer economic diversification opportunities, reducing reliance on seasonal tourism and fostering the growth of a green industrial base.

The county's development strategies emphasize sustainable tourism, renewable energy integration, and eco-friendly transport, aligning seamlessly with hydrogen adoption initiatives. While challenges remain, such as the high initial costs of infrastructure development, limited local expertise, and seasonality in maritime activity, these can be mitigated through training programs, international collaboration, and leveraging EU funding opportunities.

Hydrogen integration also presents several opportunities. High-traffic ferry routes and a strong maritime tourism sector provide an ideal platform for pilot projects. EU programs like Horizon Europe, Interreg, and the European Green Deal can support the necessary infrastructure investments. By positioning itself as a leader in hydrogen-powered maritime transport, Šibenik-Knin County can attract investments, reduce emissions, and contribute to long-term economic and environmental resilience, solidifying its role as a pioneer in sustainable maritime solutions.

2.3. Zadar County

Zadar County's strategic position as a transportation nexus makes it an ideal pilot region for hydrogen-powered maritime routes connecting the Croatian mainland and islands. Its central location along the Adriatic Sea establishes it as a key maritime hub, linking Croatia to neighboring countries and facilitating connections to its many islands.

Zadar County's geographical importance stems from its central position on the eastern Adriatic coast, which allows it to serve as a vital connector for domestic and international maritime traffic. The Port of Zadar (Gaženica) stands out as a major ferry port with modern infrastructure tailored to passenger and cargo services. Recognized for its advanced logistics facilities and commitment to sustainable technologies, Gaženica is well-positioned to become a central hub for hydrogen refueling. In addition to the main port, smaller ports such as Biograd na Moru, Sali, and Preko play crucial roles in supporting regional connectivity, inter-island traffic, and local economies, making them ideal candidates for hydrogen-powered ferry integration.

The county's maritime transport infrastructure is extensive, featuring a robust ferry network managed by operators like Jadrolinija and private companies. This network connects the mainland to over 300 islands, including Pag, Dugi Otok, and Ugljan, ensuring frequent passenger and cargo services. Recent infrastructure upgrades across several ports aim to accommodate larger and more efficient vessels, aligning with the county's sustainability goals and preparing for hydrogen adoption. Future proposals include the modernization of dockside facilities with renewable energy-powered charging stations and hydrogen refueling points, as well as the implementation of digital systems for efficient port management and real-time emissions tracking.

The hydrogen potential in Zadar County is immense, particularly given its strategic location and existing infrastructure. Gaženica Port is uniquely suited to serve as the central hub for hydrogen fueling stations, leveraging its ability to handle high traffic volumes and advanced facilities. Smaller ports, with their frequent and short inter-island routes, provide opportunities for localized hydrogen solutions. The integration of hydrogen-powered ferries across these routes would significantly reduce emissions while aligning with EU green transport objectives.

Zadar County's renewable energy capacity further supports its readiness for hydrogen adoption. Solar and wind farms near Obrovac and Nin are capable of generating the renewable electricity needed for green hydrogen production. Local industries, including shipbuilding and logistics, present opportunities for partnerships to accelerate the development of hydrogen infrastructure. The county's shipyards are well-equipped to support retrofitting projects and construct hydrogen-powered vessels, driving maritime innovation and bolstering the local economy.

Economic diversification is another key advantage of hydrogen integration. Investments in hydrogen technologies can reduce reliance on seasonal tourism by fostering a year-round industrial base, creating new job opportunities in the green technology sector. These efforts align seamlessly with Zadar County's regional development plans, which prioritize renewable energy, green tourism, and eco-friendly transport solutions.

While challenges such as high infrastructure costs, limited local expertise in hydrogen technologies, and seasonal demand fluctuations exist, they can be mitigated through targeted training programs, knowledge exchange initiatives, and international collaboration. Moreover, Zadar County is well-positioned to leverage EU funding programs such as Interreg, Horizon Europe, and the European Green Deal to finance green maritime initiatives.

The county also has significant opportunities to establish itself as a leader in hydrogen-powered maritime transport. High-traffic ferry routes, such as Zadar to Dugi Otok, offer ideal conditions for pilot projects showcasing hydrogen-powered vessels. By pioneering these sustainable initiatives, Zadar County can enhance its reputation, attract investments, and contribute to a greener and more resilient maritime sector.

Through its strategic location, advanced infrastructure, and commitment to sustainability, Zadar County is poised to play a leading role in the adoption of hydrogen-powered maritime transport. This initiative not only supports environmental protection but also drives long-term economic growth and innovation, positioning the region as a model for sustainable maritime solutions in the Adriatic and beyond.

2.4. Friuli-Venezia Giulia Region

Friuli-Venezia Giulia, located in northeastern Italy, combines advanced industrial capacities with significant maritime activities, making it an ideal candidate for early adoption of hydrogen-powered maritime solutions. Its strategic position as a maritime and economic hub in the Adriatic region, along with its well-developed ports and industrial infrastructure, reinforces its potential as a leader in sustainable maritime innovation.

Geographically, Friuli-Venezia Giulia borders Austria, Slovenia, and the Adriatic Sea, serving as a critical gateway between Central Europe and the Mediterranean. Its coastal location and strong international connections make it a vital node for trade and passenger transport. The Port of Trieste, Italy’s largest commercial port, is a key feature of the region. Known for its deep-water capacity and extensive logistics network, Trieste is well-suited to host hydrogen fueling infrastructure and serve as a major hub for hydrogen-powered maritime activities. The Port of Monfalcone complements this role, focusing on industrial goods and regional trade, with potential for hydrogen integration in both cargo and passenger vessels. Smaller maritime terminals in Grado and Lignano Sabbiadoro support passenger ferries and nautical tourism, presenting additional opportunities for hydrogen-powered recreational transport.

The region’s maritime transport infrastructure is extensive, with high-traffic shipping routes connecting Friuli-Venezia Giulia to the Adriatic, Central Europe, and international destinations. Ferry services between Trieste and neighboring countries like Slovenia and Croatia highlight the region’s role in cross-border maritime connectivity. The Port of Trieste, equipped with advanced cargo-handling and logistics systems, provides an ideal foundation for integrating hydrogen technologies. Similarly, modern facilities in Monfalcone and Grado are well-positioned to accommodate hydrogen fueling for smaller vessels, further supporting the transition to sustainable maritime transport.

Friuli-Venezia Giulia is actively preparing for hydrogen-ready infrastructure. Trieste, as a major commercial hub, is ideally suited for the establishment of large-scale hydrogen production and distribution facilities, while smaller ports such as Grado offer potential as pilot sites for hydrogen-powered ferries and recreational boats. Planned developments include integrating renewable energy sources, such as solar and wind, to power hydrogen production, ensuring a sustainable energy supply for maritime activities. The expansion of port facilities to support green maritime technologies is also under consideration.

The region’s renewable energy potential complements its hydrogen adoption goals. Existing wind farms and solar installations can provide the necessary energy for producing green hydrogen, while partnerships with the industrial sector—ranging from heavy machinery manufacturers to logistics companies—can accelerate the development and deployment of hydrogen technologies. Friuli-Venezia Giulia's shipyards are also equipped to retrofit vessels for hydrogen fuel and construct new hydrogen-powered ships, supporting maritime innovation and expanding the local economy beyond traditional industries.

Investments in hydrogen technologies offer significant economic opportunities for Friuli-Venezia Giulia. These advancements can diversify the regional economy, reduce reliance on traditional industries, and create new jobs in green technology sectors. The region's development plans, which emphasize environmental sustainability, renewable energy, and innovation, align seamlessly with the adoption of hydrogen-powered solutions, further strengthening its leadership in green transport initiatives.

Despite the challenges posed by the high costs of infrastructure development and a limited local knowledge base in hydrogen technologies, Friuli-Venezia Giulia can leverage training programs and international collaborations to address these gaps. Additionally, the region is well-placed to attract EU funding through programs like Horizon Europe and the European Green Deal, ensuring financial support for its green maritime initiatives.

The region's strategic location and proactive policies position it as a leader in sustainable maritime transport. High-volume ferry routes between Trieste and neighboring regions offer ideal platforms for deploying hydrogen-powered vessels. By pioneering these solutions, Friuli-Venezia Giulia can enhance its reputation, attract investments, and contribute to reducing emissions in the Adriatic region.

With its advanced infrastructure, renewable energy capacity, and commitment to sustainability, Friuli-Venezia Giulia is poised to play a pivotal role in implementing hydrogen-powered maritime solutions. These initiatives not only support environmental protection but also drive long-term economic growth and innovation, solidifying the region's position as a leader in green maritime transport.

2.5. Emilia Romagna Region

Emilia-Romagna, a leading industrial and economic region in northern Italy, is well-positioned to lead the transition to hydrogen-powered vessels and integrate sustainable maritime practices. Its advanced maritime infrastructure, coupled with a strong focus on sustainability, makes it an ideal candidate for hydrogen-powered maritime initiatives in the Adriatic region.

Located along the northern Adriatic coast, Emilia-Romagna serves as a vital economic and transportation corridor between Italy and Eastern Europe. The Port of Ravenna, one of Italy's most important commercial and industrial ports, is central to the region's maritime activities. Specializing in bulk cargo, containers, and energy products, Ravenna is a major logistical hub with significant potential for developing hydrogen infrastructure. Additionally, smaller ports such as Cesenatico and Porto Garibaldi support fishing, passenger transport, and nautical tourism, creating opportunities for integrating hydrogen-powered vessels into local maritime operations.

The region’s maritime transport infrastructure provides a strong foundation for hydrogen adoption. The Port of Ravenna connects Emilia-Romagna to key destinations in Europe and the Mediterranean, offering frequent ferry and cargo services to other Adriatic ports. Equipped with modern terminals and advanced logistics systems, the port is well-prepared to support green technologies, including hydrogen refueling. Smaller maritime terminals also have the potential to integrate hydrogen fueling solutions for local fishing and recreational vessels, extending the reach of sustainable practices across the region.

Emilia-Romagna is actively preparing for hydrogen-ready infrastructure. Ravenna’s industrial and maritime facilities make it an ideal location for establishing hydrogen production and distribution hubs. Future regional plans include renewable energy projects, such as offshore wind farms, to power green hydrogen production facilities, reducing reliance on fossil fuels and ensuring sustainability in maritime transport. Smaller ports, with their localized operations, are also well-suited for pilot projects involving hydrogen-powered vessels.

The region’s renewable energy potential and industrial strength further enhance its readiness for hydrogen adoption. Renewable energy initiatives, particularly offshore wind farms, provide a strong foundation for producing green hydrogen. Emilia-Romagna’s robust industrial base, which includes engineering and energy companies, offers numerous opportunities for developing and deploying hydrogen technologies. The region’s shipyards and industrial facilities are also well-equipped to support the retrofitting of existing vessels and the construction of new hydrogen-powered ships, fostering innovation in green maritime technologies.

Economic diversification is a key benefit of hydrogen integration in region. Investments in hydrogen technologies can reduce reliance on traditional industries, expand the regional economy, and create new opportunities in green technology sectors. These initiatives align closely with regional policies that prioritize renewable energy, sustainable transport, and environmental protection, ensuring a cohesive approach to hydrogen adoption.

While challenges such as high infrastructure costs and limited expertise in hydrogen systems exist, Emilia-Romagna is well-positioned to overcome these obstacles. Partnerships with international experts and knowledge exchange programs can address the knowledge gap, while EU funding through programs like Horizon Europe and the European Green Deal can support the development of hydrogen infrastructure and research.

The region’s proactive approach to sustainability and its strategic maritime position provides opportunities to establish Emilia-Romagna as a leader in green maritime transport. Pilot projects focusing on routes connecting Ravenna with other Adriatic ports would showcase the potential of hydrogen-powered vessels and set a benchmark for other regions. By adopting these innovative solutions, Emilia-Romagna can enhance its reputation, attract investments, and contribute to long-term environmental and economic resilience.

Emilia-Romagna’s industrial capabilities, advanced maritime infrastructure, and strong commitment to sustainability make it a pivotal player in the adoption of hydrogen-powered maritime solutions. This transition not only supports environmental protection but also drives innovation and economic growth, positioning the region as a leader in the green transformation of the Adriatic maritime sector.

3. Current State of Maritime Transport

Below is an analysis of the current state of maritime transport.

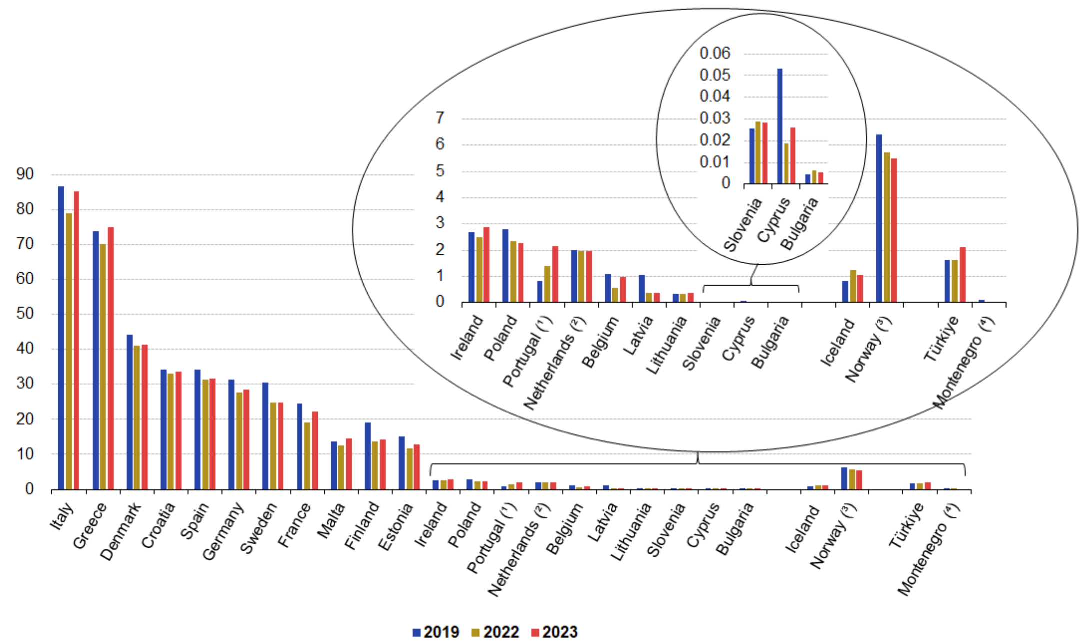
3.1. Maritime Traffic and Mobility Data

Maritime transportation has long been a cornerstone of the European Union's economic development and trade relations, both globally and within its internal market. At the heart of this system are seaports, which play a pivotal role in facilitating freight and passenger flows. Over the years, the EU has increasingly emphasized sustainability in maritime operations, as reflected in the Marine Strategy Framework Directive (MSFD). This directive establishes a legally binding, ecosystem-based approach to protect marine environments while supporting economic and social activities tied to maritime industries.

Historically, EU ports were primarily focused on freight trade. However, the growing demands of the passenger transportation sector have driven significant diversification. Today, many ports are adapting their infrastructure and operations to accommodate the expanding tourism and passenger transport industries. This evolution is evident in the increasing activity of cruise ships, RO-RO ferries, and high-speed vessels. Annually, approximately 400 million passengers embark and disembark at European ports, even considering fluctuations caused by the pandemic. Italy leads the EU in passenger transport, with Croatia ranking fourth (Figure 1).

This diversification of port services, combined with the significant share of seaborne passenger transport held by Italy and Croatia, underscores the need for a detailed analysis of maritime transport routes within and between these countries. Such an analysis aims to identify technical solutions for the decarbonization of this critical sector. By focusing on sustainability, the analysis will provide valuable insights for stakeholders to establish standards and improve service quality in technical, operational, and organizational aspects.

Figure 1 Total number of seaborne passengers embarked and disembarked in EU ports in 2019, 2022, and 2023 (in million)



Note: countries are ranked based on 2023 data. No transport of passengers in Romania.
(¹) Break in time series in 2020 and 2023 because data coverage improved.
(²) Data exclude cruise passengers.
(³) Data on international maritime passenger transport only.
(⁴) 2023 data not available. Data exclude cruise passengers.
Source: Eurostat (online data code: mar_mp_aa_cph)

eurostat

Maritime Traffic in the Adriatic Sea

The Adriatic Sea serves as a vital corridor for maritime transport, connecting the coasts of Croatia and Italy and facilitating trade and tourism with neighboring regions. It is characterized by dense maritime traffic (Figure 2), especially during the summer, with numerous regional and cross-border routes catering to passenger and freight transport. Ports such as Rijeka, Split, and Zadar in Croatia and Trieste, Venice, and Ancona in Italy form the backbone of this network, serving millions of passengers and handling significant volumes of goods annually.

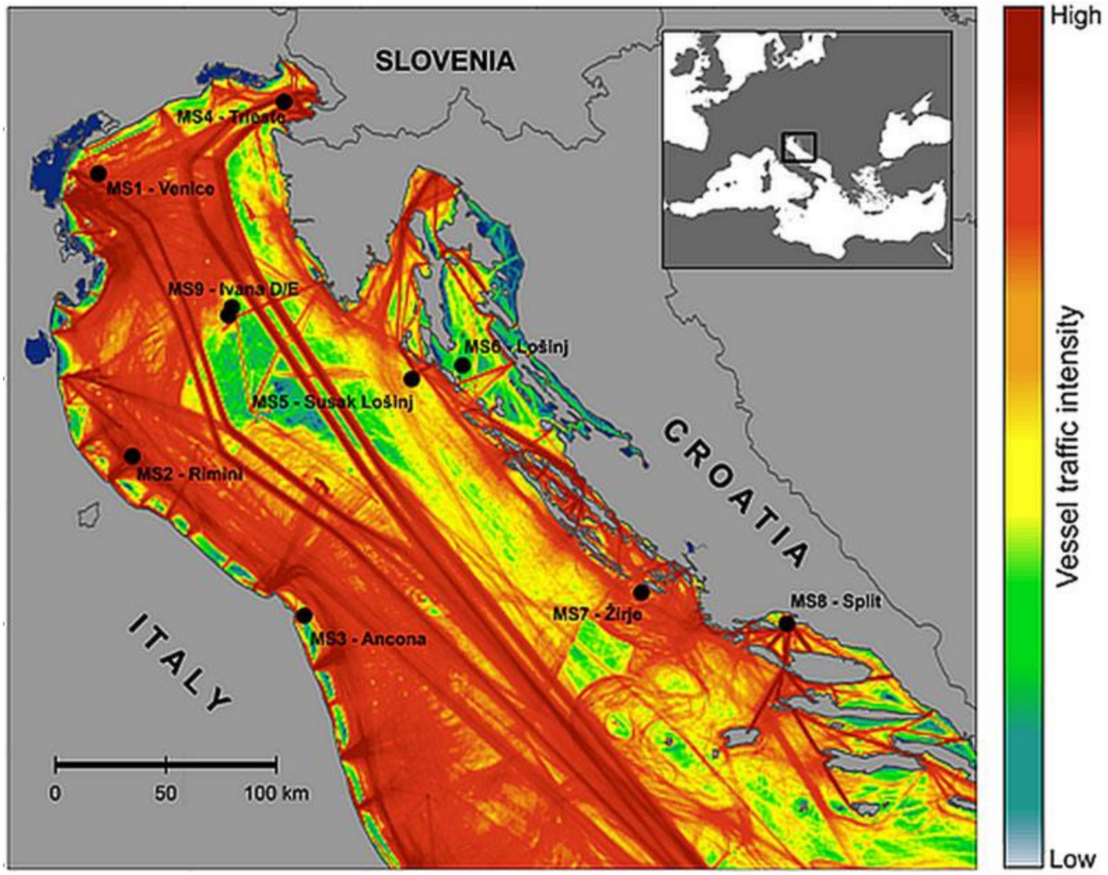
- Croatian Ports

The Port of Rijeka, Croatia’s largest and most significant port, plays a crucial role in freight logistics, handling over 13 million tons of cargo annually, including containerized goods, bulk commodities, and vehicles. It is also a key link in international trade routes, connecting Central Europe with the Mediterranean. Ports like Split and Zadar specialize in passenger traffic and regional connections. For example, Split sees heavy seasonal passenger flows due to its proximity to popular tourist destinations like the islands of Hvar and Brač. Dubrovnik, primarily known for its role in cruise tourism, accommodates over 1.5 million passengers annually during peak seasons, reinforcing its importance as a tourism hub.

- Italian Ports

On the Italian side, the Port of Trieste serves as a gateway to Central Europe, handling over 62 million tons of freight annually, including oil, coffee, and bulk cargo. Venice and Ancona are critical for passenger and ferry traffic, connecting Italy with Croatia and other Adriatic destinations. The Ancona-Split route, for instance, is one of the busiest cross-border connections, serving both passengers and freight. These ports also play a significant role in the cruise industry, hosting millions of passengers each year.

Figure 2 Vessel traffic intensity in the Adriatic sea[1]



Key Data on Maritime Traffic and Routes

Seasonality is a defining feature of Adriatic maritime traffic, with passenger volumes peaking during the summer months due to tourism. Croatia alone recorded over 32 million ferry passengers in 2022, with significant contributions from routes like Zadar-Pula and Split-Dubrovnik. On the freight side, ports such as Rijeka and Trieste are expanding their container terminals to meet growing demands for intermodal connectivity.

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[1] Petrizzo, A., Barbanti, A., Barfucci, G. et al. First assessment of underwater sound levels in the Northern Adriatic Sea at the basin scale. Sci Data 10, 137 (2023). https://doi.org/10.1038/s41597-023-02033-1

To support the analysis of maritime routes under the TransH2 project, a systematic three-step process is being implemented:

- Initial Screening: Mapping maritime routes along the Italian and Croatian coasts, as well as cross-border connections, using data from the Interreg MIMOSA project and other sources.
- Preliminary Selection: Evaluating routes based on criteria such as vessel type, passenger flow, traffic intensity, and environmental considerations.
- Stakeholder Consultation: Presenting shortlisted routes to stakeholders to identify the three most promising routes for further evaluation.

The Role of Ravenna in Maritime Mobility

The Port of Ravenna is a strategic hub in cross-border maritime routes, connecting Italy to destinations in Asia, the Middle East, and Eastern Europe. In 2023, it handled approximately 28 million tons of goods, with a notable increase in container traffic driven by rising demand for agri-food and industrial products. While passenger numbers remain lower compared to freight, the port has experienced modest growth in the cruise sector, which has positively impacted local tourism and the economy.

The port’s intermodal network, which integrates maritime, rail, and road transport, enhances logistical efficiency and reduces reliance on trucks, fostering sustainable mobility. Start Romagna, the region’s primary public transport operator, supports port activities through intermodal services, improving the efficiency of logistics and reducing the environmental footprint of heavy traffic.

Ravenna has initiated several measures to align with EU sustainability goals:

- Energy Efficiency: Replacing outdated equipment with low-energy consumption machinery.
- Alternative Fuels: Promoting the use of low-emission fuels such as liquefied natural gas (LNG).
- Environmental Monitoring: Implementing advanced systems for monitoring air quality and noise pollution.

3.1.1 Initial Screening of Maritime Routes Along the Eastern Italian and Croatian Coasts

As previously mentioned, the initial screening of regional and international maritime routes on the Adriatic Sea was performed based on data available from the previous Italy-Croatia Interreg project MIMOSA and from online sources. The latter mainly consist of the line operators’ websites, including ACTV Ferry Boat, Jadrolinija, Krilo, TP Line, and G&V Line Zadar, as well as other relevant sources such as Ferry Croatia, Croatia Ferries, and Direct Ferries.

In order to have a big picture about the spatial distribution of the first screened routes throughout the Adriatic Sea, it is possible to divide the sea into three major regions, named

North, Middle, and South Adriatic, as observed in Figure 3. From the 54 screened routes, 44% are concentrated in the North Adriatic, 52% are concentrated in the Middle Adriatic, and only 4% are located in the South Adriatic, which is a statistic data that confirms in fact the first idea about the location of the routes with higher probability of interest by the stakeholders: North and Middle Adriatic.

Figure 3 Division of the Adriatic sea into major regions

The following subsections present the 54 screened routes, but divided by route type, i.e., whether it is an Italian regional route (ITA-ITA), a Croatian regional route (CRO-CRO), or a cross-border international route (ITA-CRO). It is important to keep in mind that, in the tables presented in the next subsections, the data regarding frequency, passenger flow, distance, and travel time refer to a one-way trip for each route.

3.1.2 Italian Regional Routes (ITA-ITA)

The region of the Venice lagoon in Italy is one of the regions of Italy with most intense maritime traffic. In fact, the region of the Venice port present greenhouse gas emission levels that are around three times higher than those of other important ports in the region, such as

Trieste and Rijeka ports[2]. That is one of the reasons why three routes in the same Venice lagoon region: Tronchetto–Lido, Punta Sabbioni–Lido, and Pellestrina–Lido were selected (Table 1).

The gathering of more reliable data is still in progress; however, it is possible to see that the Tronchetto–Lido route is a very demanding connection in terms of travel frequency. It connects the main Venice Island, where vehicles arrive through the Libertà Bridge, to the Lido island, which is the home for about 14,000 people and a touristic hot-spot. The Ravenna – Brindisi – Catania (Table 1) route was a connection identified in the MIMOSA project which has a frequency of 3 times per week, passenger flow intensity of 862 per year, a distance of about 645 nautical miles, and the total travel time of 22 hours. The vessel type for all the four routes is Roll-on/Roll-off (RO-RO).

Table 1 Details about the screened Italian regional routes

Route	Route type	Vessel type	Frequency	Passenger flow	Distance (NM)	Travel time (h)	Ships name on passenger line
Ravenna-Brindisi-Catania	ITA-ITA	RO-RO	3/w	862	645	42	Eurocargo Catania
Troncheto-Lido	ITA-ITA	RO-RO	161/w	-	3.5	0.67	Metamauco/Lido di Venezia
Punta sabbioni – Lido	ITA-ITA	RO-RO	252/w	-	1	0.16	
Pellestrina - Lido	ITA-ITA	RO-RO	252/w	-	1.5	0.41	Ammiana

Abbreviation: w (week)

In 2023, the Port of Trieste handled approximately 55.6 million tons of cargo, a decrease of 3.42% compared to the previous year. The total volume handled in the port of Monfalcone was 3.83 million tons, with a slight decline of 0.38%.

3.1.3 Croatian Regional Routes (CRO-CRO)

The first screening of the Croatian regional routes resulted in 34 connections, from which 32% are in the North Adriatic region, whereas 68% in the Middle Adriatic region. Table 2 presents the 34 mentioned routes, which are sorted from the highest to the lowest annual passenger

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[2] Topic, T., Murphy, A. J., Pazouki, K., & Norman, R. (2023). NOx Emissions Control Area (NECA) scenario for ports in the North Adriatic Sea. Journal of Environmental Management, 344, 118712. https://doi.org/10.1016/j.jenvman.2023.118712

flow intensity. As observed, the top three passenger flow intensity routes are Valbiska – Merag, Misnjak – Stinica, and Prizna – Zigljen, ranging from about 940,000 to 1,140,000 passengers per year, performing the connection on board of RO-RO vessels in a travel time of around 20 minutes. The frequency of service ranges from 83 to 161 times per week, covering a distance between 2 and 6 nautical miles, in the North Adriatic region.

By extending the list to the top ten routes in terms of passenger flow intensity, only one more route will be added to the North region: Porozina – Brestova. The other six routes are located in the Middle Adriatic region. In this case, the passenger flow intensity ranges from about 360,000 to 730,000 on board of RO-RO vessels travelling distances from 2 to 24 nautical miles within an average of 40 minutes travel time. The service frequency for these routes is pretty wide, ranging from 21 to 154 times per week, which are not as frequent as the top three routes, however it can be considered as fairly high intense traffic connections.

Another important aspect of these routes (considering now all the 34 routes), for what concerns the vessel type, is that 23% of the connections are operated with passenger-only vessels (or catamarans), while the other routes are operated with passenger-only and/or RO-RO vessels.

Table 2 Details about the screened Croatian regional routes

ASR	Route	Route type	Vessel type	Frequency	Passenger flow	Distance (NM)	Travel time (h)	Ship's name on passenger line
N	Valbiska – Merag	CRO-CRO	RO-RO	83-91/w	1142556	6	0.41	**Illovik**
N	Misnjak - Stinica	CRO-CRO	RO-RO	91-161/w	954711	2	0.33	**Rapska Plovidba**
N	Prizna - Zigljen	CRO-CRO	RO-RO	84-147/w	943260	4	0.25	
M	Korcula - Orebic	CRO-CRO	RO-RO	98-154/w	735503	2	0.25	**Sveti Krsevan**
M	Split – Stari Grad	CRO-CRO	RO-RO	21-42/w	714314	24	2	**Tin Ujević, Zadar**
N	Porozina - Brestova	CRO - CRO	RO-RO	84-91/w	553627	3	0.33	
M	Tkon - Biograd	CRO-CRO	RO-RO	68-133/w	455791	2	0.25	**Kijevo**
M	Split – Rogač	CRO-CRO	Passenger\RO-RO	40-48/w	370235	11	0.5 to 1	**Biokovo, Naranca**
M	Split –	CRO-	RO-RO	61-98/w	367709	10	0.83	**Hrvat**

	Supetar	CRO						
M	Sucuraj - Drevenik	CRO-CRO	RO-RO	42-77/w	366714	4	0.58	**Laslovo**
M	Vis - Split	CRO-CRO	Passenger\RO-RO	21-27/w	272562	34	1.42 to 2.33	**Petar Hektorovic,** **Karolina**
M	Ploce - Trpanj	CRO-CRO	RO-RO	21-28/w	238768	9	1	**Pelješčanka**
M	Zadar – Ošljak – Preko	CRO-CRO	RO-RO	157-196/w	230799	3	0.33	**Cres, Sveti Juraj**
M	Vodice - Prvic - Zlarin - Sibenik	CRO-CRO	RO-RO	20-26/w	228903	6	0.42 to 1.25	**Tijat**
M	Lastovo - Vela Luka - Split	CRO-CRO	Passenger\RO-RO	16-21/w	221820	65	3.25 to 4.5	**Adriana, Vladimir** **Nazor**
M	Sipan - Lopud - Kolocep - Dubrovnik	CRO - CRO	RO-RO	33-38/w	214045	14	1.08 to 1.83	**Postira, Balota**
M	Brbinj - Zadar	CRO-CRO	Passenger\RO-RO	23-34/w	206037	18	0.66 to 1.75	**Paula/, Brac**
N	Valbiska – Lopar	CRO-CRO	RO-RO	14-28/w	153107	19	1.5	**Krk**
M	Sumartin - Makarska	CRO-CRO	RO-RO	21-35/w	149750	7	0.92 to 1.25	**Ston**
M	Sobra - Praprtano	CRO-CRO	RO-RO	42/28 w	146126	6	0.75	**Valun**
M	Korcula - Prigradica - Hvar - Split	CRO - CRO	Passenger	9-49/w	109752	52	2.58 to 3.66	**Krilo Jet**
M	Vrgada - Pakostane - Biograd	CRO-CRO	Passenger	12/w	75175	8	1	**Lumbrikata,** **Vrgadinka**
M	Jesla - Bol -	CRO-	Passenger	7/w	74505	29	1.75	**Novalja**

	Split	CRO						
M	Krapanj - Brodarica	CRO-CRO	Passenger	107 - 94 /w	74000		0.08	**Borac**
N	Novalja – Rab – Rijeka	CRO-CRO	Passenger	28/w	69435	50		**HSC Adriana**
N	Mali Lošinj – Ilovik – Susak – Unije – Martinšćica – Cres – Rijeka	CRO-CRO	Passenger	14/w	69353	68	3	**Judita**
N	Olib – Premuda – Silba – Zadar	CRO-CRO	Passenger/RO-RO	14-10/w	61707	42	2	**Princ Zadra,** **Vladmir Nazor**
M	Rava - Mala Rava - Veli iz - Mali Iz - Zadar	CRO-CRO	Passenger/RO-RO	17/w	47115	16	1.5 to 2.5	**Anamarija, Sis**
M	Latovo - Korcula - Polace - Sobra - Sipanska Luka - Dubrovnik	CRO-CRO	Passenger	9-7/w	46267	55	3.5	**Anastazija**
M	Sibenik - Zlarin - Obonjan - Kaprije - Zirje	CRO-CRO	Passenger/RO-RO	16-19/w	43749	24	1 to 2	**Miatrade,** **Peljesacanka**
N	Ist - Zapuntel - Brgulje - Molat - Zadar	CRO-CRO	Passenger/RO-RO	14-10\w	40971	20	1 to 4	**Olea, Vladmir** **nazor**
M	Zadar – Bršanj – Rava - Zaglav	CRO-CRO	Passenger/RO-RO	14-10/w	37137	9	1.2	**Melita, Sis**

N	Zadar – Ist – Olib – Silba – Premuda – Mali Lošinj	CRO-CRO	Passenger/RO-RO	11-3/w	33438	53	1.75 to 6.45	**Krilo Eclipse,** **Vladmir Nazor**
N	Mali Losinj - Unije - Srakane Vele - Susak	CRO-CRO	Passenger	24-20/w	27284	7	0.5 to 2.5	**Judita, Premuda**

Abbreviations: w (week), ASR (Adriatic Sea region), N (North Adriatic), M (Middle Adriatic)

3.1.4 Cross-border International Routes (ITA-CRO)

For the ITA-CRO routes, 16 connections were screened (Table 3). As expected, such cross-border routes are much longer, ranging from 55 to 151 nautical miles for the A to B routes (without intermediate stops). Regarding the vessel type, only 5 routes are operated with RO-RO vessels (Split - Ancona (Jadrolinija), Split- Ancona (Snav Spa), Dubrovnik – Bari, Ancona – Zadar, and Bari – Split), while the other 11 routes are operated with passenger-only vessels. The top four connections, in terms of passenger flow intensity, carry an amount between 35,000 and 96,000 passengers per year, with a frequency up to 139 times per year. For the majority of the ITA-CRO routes, these frequencies regard mainly the summer period, between June and September, although some few routes perform a few travels during other periods of the year.

Based on all the presented routes, the next steps will concern on a preliminary selection of routes based on key criteria, including vessel type, passenger flow intensity, service frequency and environmental aspects, which will be presented to the stakeholders through an online Workshop, organized by the University of Trieste, that will take place at the beginning of January 2025. Subsequently, based on the stakeholders interests, the final three routes will be defined and further analyzed.

Table 3 Details about the screened cross-border routes between Italy and Croatia.

ASR	Route	Route type	Vessel type	Frequency	Passenger flow	Distance (NM)	Travel time (h)	Ship's name on passenger line
M	Split - Ancona (Jadrolinija)	ITA-CRO	RO-RO	139/y	96011	129	8 to 11.5	**Marko Polo**
M	Split - Ancona (Snav Spa)	ITA-CRO	RO-RO	81/y	88173	129	9 to 11.5	**Aurelia**
S	Dubrovnik – Bari	ITA-CRO	RO-RO	87/y	69049	107	6.3 to 8	**Dalmacija**

M	Ancona – Zadar	ITA-CRO	RO-RO	20/y	35941	80	7 to 9	**Zadar**
N	Poreč – Venezia (Kompas d.o.o. Poreč)	ITA-CRO	Passenger	112/y	24616	55	3	**Prince of Venice**
N	Pula – Venice (Atlas d.d. Dubrovnik)	ITA-CRO	Passenger	32/y	20663	74	3.5	**Adriatic Jet**
N	Rovinj – Venezia	ITA-CRO	Passenger	125/y	17889	60	2.75	**San Pawl, San Frangisk, Adriatic Jet**
N	Poreč – Venezia (Venezia Lines LTD)	ITA-CRO	Passenger	88/y	17784	55	3	**San Pawl**
N	Pula – Venice (Venezia Lines LTD)	ITA-CRO	Passenger	44/y	16272	74	3.5	**San Frangisk**
N	Cesenatico – Pesaro – Mali Lošinj – Novalja - Rab	ITA-CRO	Passenger	60/y	11660	136	7	**Nautilus, Don Paolo**
N	Trieste – Piran – Rovinj	ITA-CRO	Passenger	62/y	6393	45	1.75 to 2.5	**Fiammetta M,** **Sofia M**
N	Rovinj – Cesenatico	ITA-CRO	Passenger	13/y	3548	75	3.5	**Eurofast Nautilus**
M	Civitanova Marche - Split	ITA-CRO	Passenger	1/w	3033	120		**HSC Zenit**
N	Cesenatico – Pesaro – Zadar	ITA-CRO	Passenger	30/y	1169	129	5.5	**Nautilus**
S	Bari - Split	ITA-CRO	RO-	1/w		151	10	**Marko Polo**

			RO					
M	**Civitanova Marche – Isola di Hvar** **(Porto di Starigrad)**	**ITA-CRO**	**Passenger**	**2/w**	**-**	**126**		**HSC Zenit**

Abbreviations: w (week), y (year), ASR (Adriatic Sea region), N (North Adriatic), M (Middle Adriatic), S (South Adriatic).

3.2. Current Port Infrastructure and Hydrogen Potential

Ports across the Adriatic region are evolving into critical energy and innovation hubs, moving beyond their traditional roles as transportation and logistics centers to becoming key players in energy distribution, renewable energy production, and hydrogen adoption. This transformation aligns with the European Green Deal’s goal of reducing maritime emissions by 90% by 2050 and restoring oceans through zero pollution and sustainable practices.

In the **Friuli Venezia Giulia region**, three ports—Trieste, Monfalcone, and Nogaro—play a pivotal role in regional and international maritime activities.

The **Port of Trieste**, one of Italy’s largest and most significant ports, is a strategic logistics hub with deep-water facilities capable of accommodating ocean-going vessels of all sizes. Located at the intersection of the "Adriatic Route" and the 5th Pan-European Corridor, Trieste is actively modernizing its infrastructure. Investments exceeding €100 million are being directed toward cold ironing facilities, enabling ships to connect to shore-side power and reduce CO_2 emissions while docked. Additionally, the port is involved in the development of a smart grid, funded with €18 million, to upgrade the city’s electricity infrastructure to meet increased demand for clean energy. The port’s plans include hydrogen production facilities and the use of existing pipelines to transport hydrogen to Central and Eastern Europe.

The **Port of Monfalcone**, the northernmost port in the Adriatic, is also advancing its decarbonization efforts. With its strategic proximity to Central Europe, Monfalcone is deepening its access channel and exploring renewable energy options, such as offshore photovoltaic installations.

Meanwhile, the **Port of Nogaro**, which handles approximately 400 merchant ships annually, is focused on electrification and the potential integration of hydrogen-powered vessels into its operations. The Friuli Venezia Giulia region is further positioned as a critical node in the Southern Hydrogen Corridor, a 3,300-kilometer network transporting green hydrogen from North Africa to Central Europe.

These ports play a vital role not only in facilitating commercial traffic, serving as key hubs for trade with Eastern Europe and Northeast Italy while also contributing significantly to the Silk Road's connectivity with Southeast Asia, but also in driving the implementation of innovative strategies aimed at environmental sustainability. This includes a strong focus on decarbonization and the adoption of advanced energy systems to support greener and more efficient maritime operations.

In this context, particular attention has been given to the decarbonization process within the ports, with the following current targeted interventions:

- Public spending on cold ironing and smart grid (over 100 million €), both in Trieste and in Monfalcone

This investment includes the construction of cold ironing facilities (a technology that allows ships to shut down their engines while docked, thereby reducing CO2 emissions). This infrastructure, in addition to being powered by photovoltaic panels, is also designed to be used in the future by vessels equipped with alternative energy carriers, such as hydrogen. The Eastern Adriatic Sea port Authority, together with the city of Trieste and Acegas-Aps-Amga (Hera Group), is involved in the Smart Grid, a project funded by the PNRR with €18 million. This aims to upgrade the city's electricity grid to support the increased demand for clean energy. The port's energy infrastructure will enable ships to recharge their batteries or even power their operations during their stay: therefore, the electrification of port terminals and the shoreside power supply for vessels are crucial components of the port's strategy to reduce emissions. In this context, the FVG Region has recently awarded contracts for the construction of a key electrification system in Port Nogaro as well.

- Public spending on photovoltaic

Renewable energy initiatives are being explored, such as offshore and onshore photovoltaic installations and floating solar panels next to the port of Trieste, in cooperation with Luka Koper.

- Public spending on railways

Ports are implementing systems to better manage energy distribution and investing in energy-efficient technologies, such as upgrading freight transportation to railway systems, which are greener than road transport.

- Soft measures

Blue agreement between port network authority and Italian Coast Guard on bunkering fuels: invite ships' operators to change bunkering fuels that are less impacting on the environment

- Ongoing evaluations for alternative fuels small scale facilities

It will be LNG, ammonia, … This is not an assess, but an ongoing private operated driven scouting.

- Allocate land use for energy sector operator

As landlord, the ports allocate land use for energy sector, including hydrogen production plants with next PV plan, storage and distribution by the waste-to-energy plant in the industrial zone of Trieste (Acegas Aps, Amga project funded by recovery founds). Some initiatives involve using existing infrastructure, such as pipelines, for hydrogen transport, which could serve the Central and Eastern European markets in the future.

Strategies and investments for the future include:

- Land allocation for energy sector operators

The port plan includes the designation of specific areas for the energy sector, encompassing the production, storage, and distribution of green hydrogen generated from renewable sources. This infrastructural support aims to promote the energy transition by fostering sustainable production and efficient distribution.

- Role as a community builder and facilitator for public and private stakeholders

The Port Authority is committed to fostering collaboration among stakeholders for the import of green hydrogen. It is anticipated that, in the future, specially equipped vessels will transport hydrogen, complementing and expanding the current pipeline transportation network.

- Exploring the reuse of existing infrastructure by local private stakeholders

Private stakeholders in the region are evaluating the possibility of utilizing an existing pipeline network, approximately 700 km long, that connects the region to Bavaria, the Czech Republic, and Slovakia. This approach would leverage existing infrastructure for green hydrogen transport, expanding access to markets in Central and Eastern Europe.

It is worth noting that the Southern Hydrogen Corridor (*SoutH2 Corridor*), connecting key hydrogen demand hubs in Europe and transporting green hydrogen from North Africa to Europe, will pass through the Friuli Venezia Giulia Region, span approximately 3,300 km and partially use existing infrastructure adapted for hydrogen transport.

The Friuli Venezia Giulia Region is also promoting the use of new energy carriers, including hydrogen, not only through direct interventions but also by actively participating in strategic planning activities. At the regional level, a process of assessing actions to be included in the new Regional Energy Plan has been initiated, while at the level of the Port Authorities, there is strong collaboration in the drafting of the strategic documentation for the port system. These initiatives highlight the Region’s commitment to ensuring a more sustainable and innovative future for the port sector, with a particular focus on the integration of new energy technologies.

The main ports of **Emilia-Romagna**, including Ravenna, Cesenatico, Comacchio, and Rimini, have distinctive features and well-established infrastructure, each playing a specific role in the regional economy. Specifically, the **port of Ravenna** is the region’s primary commercial hub, handling a wide range of goods, including chemicals, construction materials, cereals, fertilizers, and industrial products. Thanks to its strategic location and connection to major rail and road routes, the port serves as a critical point for distribution to central and eastern Europe.

The current fueling systems at regional ports mainly rely on fossil fuels, with increasing attention toward more sustainable solutions. Studies and projects have been initiated to integrate alternative fuels, such as liquefied natural gas (LNG), and to prepare for the adoption of hydrogen as the primary energy carrier. In particular, the port of Ravenna is developing a plan to modernize its energy infrastructure, promoting practices that reduce CO2 emissions.

At present, hydrogen and alternative fuel refueling infrastructure is limited, but potential expansion sites have been identified, such as adjacent industrial areas and underutilized port zones. These interventions could accelerate the integration of green technologies and address the growing demand for sustainability in the maritime sector. Collaborations with research institutions and international partners further stimulate innovation and technological development at the port.

Electrification is one of the pillars of the ecological transition at the port of Ravenna. Among the most significant interventions:

- COLD IRONING: the implementation of systems for providing electrical power to moored ships, reducing the use of diesel generators. This investment includes the construction of cold ironing infrastructure, a technology that allows ships to turn off their engines while docked, thus reducing CO2 emissions. This infrastructure, which is also powered by photovoltaic panels, is designed to be used in the future by ships equipped with alternative energy carriers, such as hydrogen. The port's energy infrastructure will allow ships to recharge batteries or power operations during their stay in port.
- ADVANCED ELECTRICAL INFRASTRUCTURE: upgrading of electrical grids to support the growing energy demand of the terminals. The installation of a 20 MWp photovoltaic system is planned, with an investment of approximately 30 million euros, 20 million of which are financed by the "PNRR Green ports" initiative. The project, scheduled for completion by 2026, will be developed on an area of approximately 36 hectares, with an installed capacity of around 20 MWp and an annual production of about 36 GWh, equivalent to more than 1,830 annual hours, preventing the release of 15,000 tons of CO2 per year.
- ELECTRIC VEHICLES: the introduction of electric vehicles for logistics and freight handling operations, as well as the implementation of electric buses for public transport services to the port facilities and cruise terminal, will result in 31 operational electric buses in Ravenna by 2025, representing about 40% of the urban fleet.

These projects are co-financed by European and national funds to ensure the economic sustainability of the initiatives.

Hydrogen technology in the maritime sector represents a promising opportunity to reduce environmental impact and improve energy efficiency. The port of Ravenna has already initiated efforts to develop infrastructure for the production and storage of green hydrogen, utilizing renewable sources such as solar and wind energy. Innovative projects like "HYDROGEN VALLEY RAVENNA", involving public institutions, universities, and private companies, aim to create an integrated ecosystem where hydrogen can become the centerpiece of the port's energy transition. This includes the installation of state-of-the-art electrolyzers to ensure efficient and sustainable hydrogen production, which can be used to power low-emission ships as well as port vehicles and cargo handling equipment.

In addition to propulsion, hydrogen is viewed as a solution for energy storage and for balancing demand and supply during peak periods. Hydrogen represents one of the most promising innovations for the port of Ravenna. The strategies being implemented include:

- local hydrogen production through the installation of electrolyzes powered by photovoltaic and wind systems near the port;
- testing hydrogen-powered vehicles and machinery, such as cranes and forklifts, to gradually replace those powered by fossil fuels;
- creation of hydrogen refueling stations within the port area and at key regional logistics hubs to encourage the use of hydrogen-powered heavy vehicles;
- international collaborations with other European ports to share best practices and develop common standards for the use of hydrogen.

The port of Ravenna is actively pursuing decarbonization through targeted measures to minimize its environmental footprint. Key interventions include:

- Energy Efficiency: Upgrading to low-energy consumption machinery and replacing outdated equipment.
- Promotion of Alternative Fuels: Encouraging the use of low-emission fuels, such as liquefied natural gas (LNG).
- Environmental Monitoring: Implementing systems to monitor air emissions and noise pollution.

The port of Ravenna is implementing an ambitious strategic plan for the future, which includes expanding infrastructure, such as dredging to accommodate larger vessels and strengthening container terminals. Digitalization plays a central role, with the adoption of advanced technologies to optimize traffic management and logistics operations. Additionally, public-private partnerships will be established to involve investors in financing infrastructural and sustainable projects. Research and development will be given significant attention, particularly focusing on innovative projects related to hydrogen and renewable energy.

In 2023, the port of Ravenna handled about 28 million tons of goods, with significant growth in container traffic and agri-food products, with major markets in Asia, the Middle East, and Eastern Europe. Regarding mobility, the port is integrating its infrastructure with the regional and national rail network, promoting intermodal transport to reduce reliance on trucks and improve logistical efficiency. The port of Ravenna represents a virtuous example of sustainable development and innovation in Italy, and through its decarbonization, electrification, and hydrogen promotion initiatives, along with ambitious strategic plans, it is positioning itself as a crucial hub for the future of logistics and the ecological transition in Emilia-Romagna.

In **Primorje-Gorski Kotar County**, the Port of Rijeka stands as Croatia's largest and most strategically significant maritime hub, playing a vital role in the Trans-European Transport Network (TEN-T). With ongoing modernization efforts, the port is focusing on energy efficiency and decarbonization to align with the European Green Deal's environmental goals. Key projects include the implementation of cold ironing systems, which allow ships to connect to shore-side power while docked, significantly reducing CO_2 emissions. Plans are also in place to integrate renewable energy systems, leveraging the port's geographical advantages to transition toward greener operations.

The nearby LNG terminal on Krk Island, already a critical energy hub for Croatia and its neighboring regions, presents a prime opportunity for adaptation into a hydrogen production, storage, and distribution facility. Its strategic location and existing infrastructure position it as a potential leader in green hydrogen initiatives. Smaller ports on islands like Krk, Cres, and Lošinj are integral to regional connectivity and tourism, and they are being considered for pilot projects involving hydrogen-powered vessels and refueling stations. These smaller ports also support eco-tourism and inter-island trade, making them ideal testbeds for sustainable maritime innovations.

In **Šibenik-Knin County,** the Port of Šibenik serves as a multifunctional hub supporting both industrial and tourism-related maritime traffic. Recent investments in port electrification and renewable energy infrastructure aim to reduce emissions and facilitate hydrogen adoption. The county's smaller ports, such as Vodice, Primošten, and Murter, are critical to regional transport networks and are undergoing evaluations for integrating hydrogen-based technologies. These efforts align with Croatia’s commitment to promoting sustainability in its maritime sector, enhancing its role as a regional leader in green transportation.

Further south in **Zadar County**, the Port of Gaženica stands out as a modern logistics and passenger hub. Recognized for its strategic role within the Adriatic maritime network, Gaženica is central to ongoing feasibility studies examining the introduction of hydrogen-powered ferries. The port’s infrastructure is also being assessed for the development of hydrogen refueling stations to support these new operations. Smaller ports such as Biograd na Moru, Preko, and Pag play a vital role in maintaining inter-island connectivity and are slated to participate in future hydrogen mobility initiatives.

The Croatian Adriatic coastline, with its dense network of regional and inter-island routes, presents an ideal environment for advancing sustainable maritime transport. The ports in this region are not only critical for freight and passenger traffic but also serve as key platforms for piloting green energy technologies. By integrating hydrogen-powered solutions and renewable energy systems, these ports are actively contributing to Croatia’s energy transition and aligning with EU-wide sustainability objectives.

Key initiatives across Croatian ports include the following:

- Cold Ironing Systems: The installation of shore-side power supply systems at major ports, such as Rijeka and Gaženica, to minimize emissions from docked vessels.
- Renewable Energy Integration: Incorporation of photovoltaic and wind power systems to produce green hydrogen and support port operations.
- Hydrogen Refueling Infrastructure: Pilot projects at strategic locations, including the LNG terminal on Krk Island, to establish hydrogen production, storage, and distribution facilities.
- Electrification of Port Operations: Modernization of cargo handling equipment and adoption of electric vehicles to reduce reliance on fossil fuels within port zones.

- Collaboration with Stakeholders: Partnerships with public and private entities to develop standards and accelerate the adoption of hydrogen technologies.

Croatia's commitment to sustainability is evident in its national strategies and regional development plans, which prioritize investments in green infrastructure, research, and international collaboration. Partnerships with Italian ports and other stakeholders across the Adriatic enhance the potential for Croatian ports to become key players in the hydrogen transition and a model for sustainable maritime innovation.

These efforts align with the strategic objectives of the European Green Deal and the EU’s mission to restore oceans and waters, addressing immediate environmental challenges while fostering long-term economic and ecological resilience. By integrating hydrogen technologies and renewable energy systems, Croatian ports are positioning themselves as leaders in sustainable mobility and critical contributors to the Adriatic region’s green energy transformation.

The shift toward decarbonized maritime transport is supported by substantial investments in cold ironing, renewable energy, and smart grid technologies. These initiatives aim to reduce emissions, modernize port infrastructure, and enable the adoption of hydrogen as a primary energy carrier. Furthermore, cross-border cooperation strengthens collaboration between public and private stakeholders, ensuring shared progress toward common sustainability goals.

By leveraging existing infrastructure, embracing innovative energy solutions, and fostering regional partnerships, Croatian ports are playing a vital role in the transition to a greener maritime sector. These transformative initiatives position them not only as hubs of sustainable mobility but also as leaders in the Adriatic region’s push for environmental and economic resilience.

3.3. Environmental Impact

Ports play a critical role in both economic activity and environmental impact, particularly in terms of greenhouse gas (GHG) emissions. Understanding the baseline emissions from port operations is essential for designing effective strategy.

The baseline data for GHG emissions in the terrestrial context of the ports of Trieste and Monfalcone for 2019 can be divided per the following emission sources:

- Electricity Consumption: 11,774.1 tons CO2eq (34.1%)
- Heating: 2,767.9 tons CO2eq (8.0%)
- Service Vehicles: 3,373.7 tons CO2eq (9.8%)
- Operational Heavy Vehicles: 13,532.0 tons CO2eq (39.2%)
- TIR Heavy Vehicles: 1,693.5 tons CO2eq (4.9%)
- Railway Locomotives: 940.3 tons CO2eq (2.7%)
- Other Sources: 443.2 tons CO2eq (1.3%)

For a total of 34,524.8 tons of CO2 equivalent.

The baseline data for GHG emissions from commercial maritime traffic in the ports of Trieste and Monfalcone for 2019 can be divided per:

- Mooring operations: 14,168.1 tons CO2eq (11.0%)
- Moored: 114,160.2 tons CO2eq (89.0%)

and per ship type:

- Bulk and General Cargo Ships: 16,158.4 tons CO2eq (12.6%)
- Container Ships: 15,020.0 tons CO2eq (11.7%)
- Passenger Ships: 10,400.0 tons CO2eq (8.1%)
- RO-RO Ships: 21,087.8 tons CO2eq (16.4%)
- Tanker Ships: 65,661.8 tons CO2eq (51.2%)

for a total of 128,328.3 tons of CO2 equivalent as maritime emissions.

Maritime transport significantly contributes to greenhouse gas (GHG) emissions in the Emilia-Romagna region, with the port of Ravenna being one of the main traffic and pollution hubs. The transition to hydrogen-powered systems is estimated to drastically reduce these emissions, contributing to the climate neutrality goals set by the European Union. This transition aligns with European and national policies aimed at reducing CO2 emissions and other pollutants, promoting sustainable solutions in the transport sector.

In addition to the direct reduction of emissions, the adoption of green hydrogen has the potential to improve air quality in urban and coastal areas near the port. Environmental impact assessments highlight that, in addition to climate benefits, the energy transition will also bring economic advantages, stimulating the creation of new jobs in the renewable energy and environmental engineering sectors. Transforming the port of Ravenna into a sustainable hub could attract investments and promote technological innovation in the region, fostering local economic growth.

Politically, the adoption of hydrogen as an alternative fuel positions the port of Ravenna as a reference model in the global energy transition. Government support and access to European funding are crucial to sustain these projects and ensure their implementation. Collaboration between public entities, private companies, and academic institutions plays a key role in advancing research and developing cutting-edge technologies. This synergy can accelerate the achievement of environmental goals and create a favorable environment for the spread of green technologies in the maritime sector.

In summary, through its strategy for the transition to green hydrogen, the port of Ravenna not only significantly contributes to the reduction of greenhouse gas emissions but also generates environmental, economic, and political benefits, strengthening the position of the Emilia-Romagna region as a leader in sustainability and innovation.

Croatia's maritime sector plays a vital role in the Adriatic region's transport network. However, this sector also contributes significantly to greenhouse gas (GHG) emissions, especially from port activities and maritime traffic.

Shipping is a large consumer of fossil fuels, so the potential for the use of hydrogen as a fuel is high. To this end, it will be necessary to build appropriate infrastructure (filling points in ports) and replace or convert existing ships.

The potential for the use of hydrogen in Croatia's maritime sector, including ferries, small ships, and boats, presents a unique opportunity to both decarbonization of the commercial shipping sector and enhancement of green tourism. This synergy between green tourism and hydrogen technology can position Croatia as a leading destination for sustainable travel in Europe.

The expected increase in renewable hydrogen consumption in maritime transport is outlined in the Study of the Development Plan and Implementation of the Croatian Hydrogen Strategy by 2050.[3] This study provides a baseline scenario and target share projections for the years 2030, 2040, and 2050, reflecting Croatia's strategic transition towards hydrogen-powered maritime mobility.

Table 4 presents the projected share and consumption of renewable hydrogen in maritime transport, alongside the Renewable Energy Directive (RED III) target for sustainable fuels in the transport sector.

Table 4 Expected Use of Renewable Hydrogen in Maritime Transport

	2030	2040	2050
Share of renewable hydrogen in total maritime transport consumption	2,65%	5%	8%
Consumption of renewable hydrogen in maritime transport	432t	784t	1200t
Target according to RED III	>1.2%		

This data highlights the gradual scaling of hydrogen adoption in the Croatian maritime sector, with a significant increase in consumption expected by 2050, in line with EU sustainability goals.

Furthermore, Figure 4 illustrates the anticipated regional growth of hydrogen use in Croatia for 2030 and 2050, providing a visual representation of the expansion trends across different sectors, as forecasted in the same study.

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[3] https://www.azu.hr/media/201nx0by/hr-h2-strategy-implementation_summary-study_final.pdf

This forecast underscores the importance of strategic investments in hydrogen infrastructure, refueling stations, and vessel retrofitting, ensuring that Croatia meets both its national hydrogen strategy objectives and EU decarbonization commitments.

Figure 4 Expected Regional Growth of Hydrogen Use in Croatia

In the Republic of Croatia, about 310 vessels larger than 100 GT participate in maritime traffic. Around 85% of these vessels are passenger ships and the rest are used for the transport of goods. There are about 120 ships in river traffic. The smallest number of these ships, around 10%, are motor freighters and motor tankers, while the largest part are non-self-propelled vessels.

An analysis of CO_2 emissions in the ports of Rijeka and Zadar was conducted as part of the SUSPORT project[4], using data from 2019 to assess the environmental impact of maritime activities. The study examined ship arrivals, energy consumption, and emission sources to provide a comprehensive overview of greenhouse gas emissions in these ports.

The analysis for port of Rijeka considered 251 ship arrivals, with the estimated total time spent in port varying significantly by vessel type. Passenger ships had an average port stay of 14.4 hours, while general cargo ships averaged 15.3 hours. However, larger vessels such as container ships and bulk carriers had significantly longer port stays, averaging 91.5 hours and 39.5 hours, respectively. The total CO_2 emissions from maritime activities in the analyzed ports amounted to 20,234.61 tonnes.

In terms of energy consumption, the majority of emissions occurred during mooring operations, which accounted for 72.02% of total emissions. This was followed by maneuvering activities, which contributed 21.98%, and anchoring operations, which accounted for 5.99%.

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[4] https://programming14-20.italy-croatia.eu/documents/2142767/2777734/D.3.2.8+TNA+Rijeka.pdf/c8cb2f34-fe88-6a25-66cb-17e1098e9996?t=1658484166865
https://programming14-20.italy-croatia.eu/documents/2142767/2777734/D.3.2.9+TNA+Zadar+%281%29.pdf/0dac5c12-4c8d-6d33-682e-c059012885eb?t=1692701201181

When emissions were categorized by ship type, container ships were identified as the largest contributors, generating 60.63% of total maritime emissions. General cargo ships accounted for 30.76%, followed by passenger ships at 4.73%, and bulk carriers at 3.83% (Table 5).

Table 5 Overall maritime emissions (CO2) in tonnes based on ship type and type of activities (2019)

Type of ship	Anchoring	Maneuvering	Mooring	Total (ship type)
Passenger	234,48	74,77	648,70	957,95
Container	2.277,34	999,93	8.991,36	12,268,63
General Cargo	1.713,27	133,75	4.377,88	6.224,90
Bulk Carrier	222,58	4,60	555,99	783,17
Total (activities)	4.447,62	1.213,05	14.573,94	20.234,61

A more detailed breakdown of emissions based on both ship type and operational activity further highlights these trends. Passenger ships produced a total of 957.95 tonnes of CO_2, with the majority of emissions occurring during mooring (648.70 tonnes). Container ships had the highest emissions, totaling 12,268.63 tonnes, with mooring accounting for 8,991.36 tonnes. General cargo ships generated 6,224.90 tonnes of CO_2, while bulk carriers contributed 783.17 tonnes.

Beyond maritime emissions, the total emissions for the analyzed port areas—including emissions from other port activities—amounted to 24,128.66 tonnes of CO_2. Moored ships remained the dominant source, contributing 60.40% of emissions, followed by anchored ships at 18.43%. Cargo handling equipment accounted for 8.17%, ships in maneuvering contributed 5.03%, and electricity consumption made up 4.16% of emissions. The lowest emissions were attributed to port vehicles, including work and cargo vehicles, which collectively contributed 3.81% of total emissions.

These findings highlight the significant environmental impact of port operations in Rijeka, particularly from moored and anchored ships. The data underscores the need for targeted decarbonization strategies, such as transition toward alternative fuels, including hydrogen and increased energy efficiency in cargo handling. Aligning with broader European sustainability objectives, these measures would help mitigate CO_2 emissions and enhance the environmental performance of Croatian seaports.

The **Port of Zadar** is a vital transportation hub with a significant volume of maritime traffic, particularly from ferries and cruise ships. In 2019, the total number of ferry departures was estimated at 7,309, while cruise ship arrivals amounted to 142. Given the city's popularity as a cruise destination, maritime emissions from moored ships represent the largest share of total emissions in the port.

The emissions data indicate that mooring emissions far exceed emissions from maneuvering. As shown in Figure 6, greenhouse gas (GHG) emissions from moored ships are nearly 19 times higher than those from maneuvering operations. While this might seem disproportionate, similar trends have been observed in other ports. For example, in 2010, the Port of Gothenburg recorded mooring emissions that were ten times greater than those from maneuvering. This discrepancy is logical given the layout of the Port of Gaženica, which is relatively open and allows for short maneuvering times. Additionally, cruise ships contribute significantly to these figures due to their high hoteling emissions while docked.

Figure 5 Share of GHG emissions by ship operation regime shows that cruisers need to be in the focus for port authorities in correlation to emissions

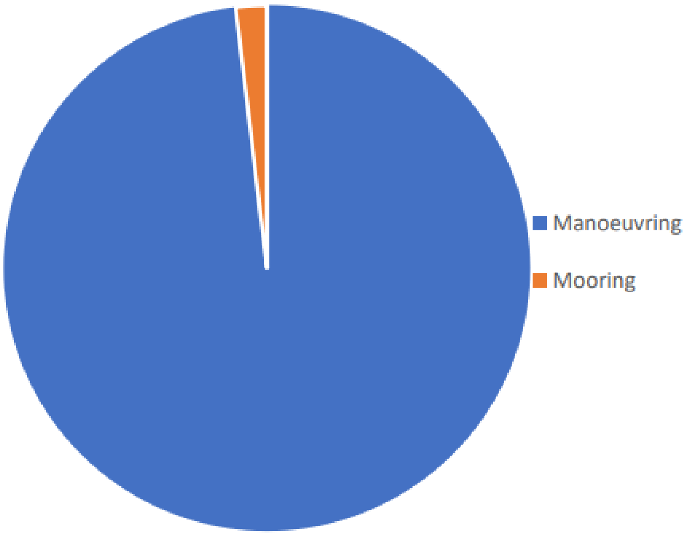


Table 7 provides a breakdown of GHG emissions from maritime operations in the Port of Zadar. The data reveal that moored ships account for 94.4% of the total emissions, while maneuvering ships contribute only 5.6%. There are no emissions from anchored ships, as the Port of Gaženica is not yet a home port for cruise ships. A spatial analysis of emissions highlights that mooring emissions are distributed across most of the port area. Other ferry docks contribute minimal emissions, with only Dock 5 being exclusively used by the ferry *Cres*.

Table 6 Summary of contributions to the production of greenhouse gases in the maritime sector, in the port of Zadar, in 2019

Category	t CO2eq	%
Anchored ships	0	0
Ships manoeuvring	223.6	5,6
Moored ships	3799.1	94,4
TOTAL	**4023.7**	**100**

Total maritime emissions in the Port of Zadar amounted to 4,023.7 tCO_2 in 2019. This is not considered a particularly high figure in the context of maritime emissions, especially when analyzed in terms of specific emissions per cruise ship call. With a predicted 197 cruise ship calls in 2021, the average emission per call is approximately 20.42 tCO_2 per cruise ship. Given these findings, cruise ships should remain a focal point for the port's sustainability efforts, particularly in the development of shore power infrastructure to reduce emissions during prolonged stays.

Aligning with the objectives of the Joint Cross-Border Strategy further integration of alternative fuels, such as hydrogen, could significantly reduce emissions in the Port of Zadar. The ongoing development of sustainable port infrastructure will be key in meeting EU climate targets and transitioning towards a greener maritime sector in the Adriatic region.

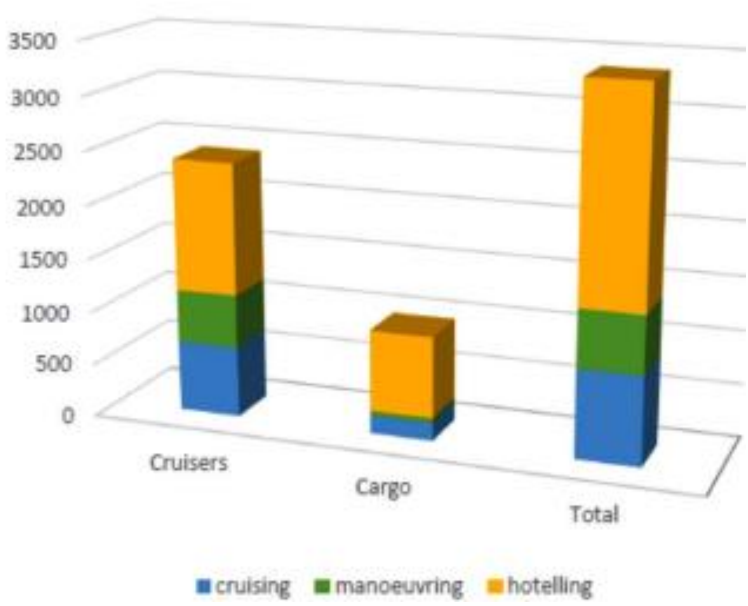
The emission inventory of maritime traffic in the Port of Šibenik has been thoroughly analyzed in a study published in the *Scientific Journal of Maritime Research 34* under the article "*Emission Inventory of Marine Traffic for the Port of Šibenik*". The study provides an assessment of harmful gas emissions from both cargo and cruise ships, using a bottom-up methodology that takes into account vessel characteristics, including engine power, fuel type, load factor, and the duration of operations such as cruising and hoteling.

According to the study, the total annual emissions for cargo ships were found to be 17.34 tons of NO_x, 1.25 tons of SO_x, 0.64 tons of VOC, and 0.56 tons of PM. The majority of these emissions originated from hoteling, where ships rely on auxiliary engines for onboard energy supply. Similarly, cruise ships were identified as significant contributors to emissions, producing higher levels of pollutants compared to cargo vessels due to their more powerful auxiliary engines and a slightly greater number of ship arrivals. The total annual emissions from cruise ships reached 38.48 tons of NO_x, 3.02 tons of SO_x, 2.07 tons of VOC, and 1.37 tons of PM.

CO_2 emissions were also analyzed, showing a total of 3,363.54 tons per year for all vessel types. Of this amount, cargo ships accounted for 968.59 tons, with 756.02 tons emitted during hotelling, 166.4 tons during cruising, and 46.18 tons during manoeuvring. In contrast, cruise ships were responsible for 2,394.95 tons of CO_2 emissions, with 1,236.23 tons generated during hotelling, 493.59 tons during manoeuvring, and 665.14 tons during cruising (Figure 7).

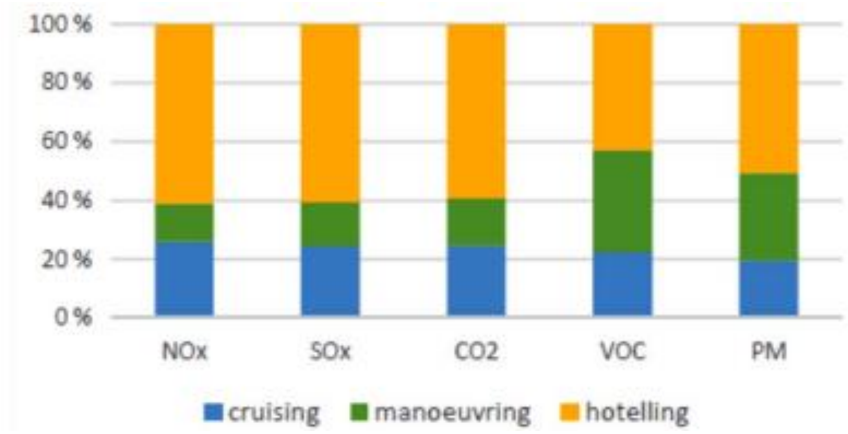
These findings confirm that a significant portion of emissions occurs when ships are stationary in port, relying on onboard power generation.

Figure 6 Total CO2 emission (tons/year)



The analysis of emission proportions by operational activity further supports these conclusions. Between 45–60% of total emissions were recorded during hoteling, while 15–30% were attributed to maneuvering and 10–25% to pilotage operations. This indicates that the majority of emissions occur when ships are docked, as their auxiliary engines remain active to sustain onboard energy needs.

Figure 7 The Port of Šibenik – emission of harmful gases from ships activities for the overall marine traffic



Overall, in 2018, marine traffic in the Port of Šibenik included 86 cruise ship arrivals and 70 cargo vessel arrivals. The total annual emissions inventory for the port, as estimated in the study, was 55.82 tons of NO_x, 4.27 tons of SO_x, 3,363.54 tons of CO_2, 2.71 tons of VOC, and

1.93 tons of PM. Passenger ships contributed approximately 70% of total annual emissions (2,439.89 tons/year), while cargo vessels accounted for the remaining 30% (988.38 tons/year). The dominance of hoteling as the primary source of emissions highlights the importance of implementing energy-efficient solutions (Figure 8).

A key measure for reducing emissions at the Port of Šibenik is the adoption of shore-side electricity, commonly known as cold ironing. This technology allows ships to connect to a land-based power supply while docked, eliminating the need to run their main and auxiliary engines. As a result, it significantly reduces greenhouse gas emissions, air pollution, and noise levels, improving overall environmental conditions in port areas.

In addition to shore power, the use of hydrogen-based energy alternatives is being explored to further support the transition toward cleaner maritime operations. By integrating these technologies, ports can enhance energy efficiency, reduce reliance on fossil fuels, and improve air quality, contributing to a more sustainable maritime sector in the Adriatic.

4. Hydrogen as Green Fuel for Maritime Transport[5]

This section provides an overview of the state of play for using hydrogen as a fuel in the shipping sector.

4.1. Production of Hydrogen

4.1.1 Hydrogen Technology Readiness

Hydrogen is gaining a lot of attention as a clean fuel since it can be generated from renewable energy through electrolysis, but hydrogen can be stored in various forms each with its own pros and cons. Fact that brings significant impact in several aspects of the maritime industry, altering radically the costs, technologies, environmental impact as well as the earning capacity of the industry.

There are already some possible technologies for storing hydrogen, including compressed gas, liquid hydrogen, and solid-state storage. In each one there are pros and cons in its application in terms of energy density, safety, and practicality for maritime applications. For long-distance transport, solutions like liquid organic hydrogen carriers (LOHC) and ammonia are more cost-effective. While LOHC systems show promise for merchant ships, onboard designs need significant development. Despite cost and storage challenges, hydrogen offers low emissions and high efficiency.

Hydrogen is a widely used, commercially available chemical. It is a building block for many chemical and pharmaceutical products, notably for the ammonia used as a fertilizer in food crops.

The global production of hydrogen in 2021 was approximately 94 million tonnes (Mt), of which only 0.04% (35,000t) was ‘green’ hydrogen produced from electrolysis (IEA, 2022). Broadly, the hydrogen was used in refineries, for fertilizer production, and in other industrial areas. For comparison, the annual consumption of conventional residual and distillate fuels by international shipping is about 285 Mt per year, or equivalent to about 95 Mt/year of hydrogen, based on its lower heating value.

4.1.2 Properties of Hydrogen

At atmospheric temperature and pressure, hydrogen is a colourless gas without a smell. Its main properties are displayed in Table 8.

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[5] Information provided in this part of the strategy are based on the main findings of the following document: “European Maritime Safety Agency (2023)“, Potential of Hydrogen as Fuel for Shipping, EMSA, Lisbon, particularly pages 15-147 applicable for the cross-border strategy of the TRANSH2 project.

Table 7 Key properties of hydrogen in comparison to MGO

Item	Hydrogen	MGO
Energy density (MJ/L)*	8.51	35.95
Lower heating value (MJ/kg)	120	42.8
Heat of vaporisation (kJ/kg)	449	250-450
Auto-ignition temperature (ºC)	585	250
Liquid density (kg/m^3)	70.8 (at -253 ºC)	840 (at 15 ºC)
Adiabatic flame temperature at 1 bar (ºC)	2127	2000
Molecular weight (g/mol)	1.007825	54
Melting point (ºC)	- 259	-26
Boiling point (ºC)	-253	154
Flash point (ºC)	N/A	60
Critical temperature (ºC)	-239.8	654.9
Critical pressure (bar)	1.30	30
Flammable range in dry air (%)	4 to 75	0.7 - 5
Item	Hydrogen	MGO
Minimum ignition energy (mJ)	0.017	**0.23**
Cetane number	N/A	**40**
Octane number	**>130**	**15-25**

* Liquid hydrogen is considered

4.1.3 Hydrogen production technologies

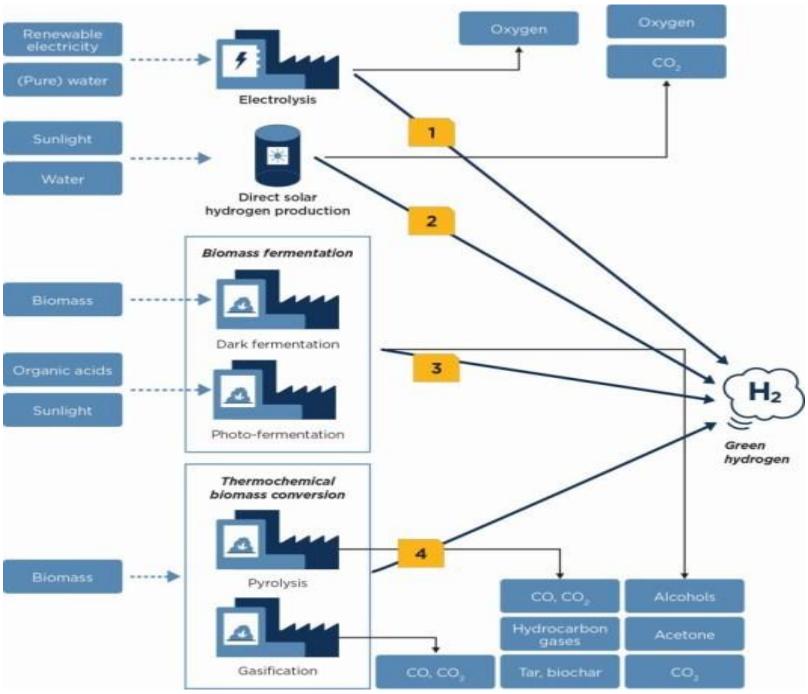
Hydrogen is increasingly recognized as a clean fuel with significant potential for decarbonizing the maritime sector, particularly as it can be produced from renewable energy sources through electrolysis. However, its adoption in maritime applications is influenced by storage methods, each with distinct advantages and challenges. The choice of hydrogen storage solutions will impact costs, technological feasibility, environmental benefits, and the overall economic viability of hydrogen-powered shipping.

Several technologies are currently available for hydrogen storage, including compressed gas, liquid hydrogen, and solid-state storage, each varying in energy density, safety, and practicality for maritime applications. For long-distance transport, alternative solutions such as liquid organic hydrogen carriers (LOHC) and ammonia present cost-effective options. While LOHC systems hold promise for merchant vessels, onboard storage and fuel system designs still require significant advancements to achieve commercial scalability. Despite challenges related to cost and storage efficiency, hydrogen remains a promising fuel due to its low emissions and high energy efficiency.

Beyond the maritime sector, hydrogen plays a fundamental role in industrial applications. It is an essential component in chemical and pharmaceutical production, particularly in the manufacture of ammonia-based fertilizers crucial for global food production. However, current hydrogen production remains predominantly fossil fuel-based. In 2021, global hydrogen production reached approximately 94 million tonnes (Mt), with only 0.04% (35,000 t) classified as 'green' hydrogen derived from electrolysis (IEA, 2022). The majority of hydrogen is consumed in oil refineries, fertilizer production, and various industrial processes. To put this in perspective, international shipping consumes approximately 285 Mt of conventional residual and distillate fuels annually, which, based on the lower heating value of hydrogen, equates to an annual demand of roughly 95 Mt of hydrogen.

Aligning with the objectives outlined in the Joint Cross-Border Strategy, the integration of hydrogen as a marine fuel requires strategic investments in infrastructure, regulatory frameworks, and technological advancements. Establishing large-scale hydrogen production from renewable sources, developing efficient and safe storage methods, and ensuring economic feasibility through policy support will be critical to accelerating its deployment in maritime transport. Hydrogen's role in the decarbonization of shipping will depend not only on its technical maturity but also on collaborative efforts to standardize its use across international and regional maritime regulations.

Figure 8 Production pathways for green hydrogen



Pathway 1 - Electrolysis

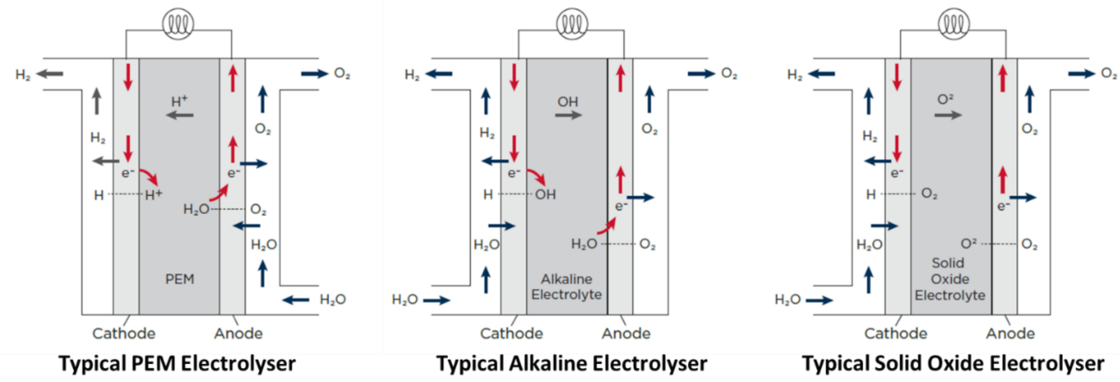
Electrolysis is the most scalable method for producing green hydrogen, using renewable electricity to split water into hydrogen and oxygen. Recognized under the EU's Renewable Energy Directive (RED) as a renewable fuel of non-biological origin (RFNBO), this process is central to the decarbonization of maritime transport and broader industrial applications.

Historically, electrolysis played a major role in hydrogen production, particularly in hydropower-based ammonia synthesis. Today, three primary electrolyzer technologies—alkaline, proton exchange membrane (PEM), and solid-oxide (SOEC)—offer varying efficiency, cost, and operational flexibility.

Electrolyzer Technologies (Figure 10):

- Alkaline Electrolysis: The most advanced and cost-effective option, with 63-70% efficiency (IEA, 2019). Durable and widely used, it relies on liquid electrolytes but is less flexible in fluctuating renewable energy conditions. 70% of global installed capacity is based on alkaline technology (IEA, 2022).
- PEM Electrolysis: More responsive to renewable energy variations but costlier due to rare earth metal requirements. It operates at 56-60% efficiency and represents 25% of installed capacity globally.
- SOEC Electrolysis: An emerging high-temperature technology with potential efficiencies of 74-81%, especially when integrated with solar power. However, it remains pre-commercial and not yet viable for large-scale deployment.

Figure 9 Electrolyser technologies currently available or under development



Typical PEM Electrolyser **Typical Alkaline Electrolyser** **Typical Solid Oxide Electrolyser**

Electrolyzers require high-purity deionized water to prevent performance degradation. Seawater desalination and purification, though necessary in some regions, contribute only 1-2% to total production costs. Post-production purification removes oxygen and water vapor to enhance hydrogen quality.

Table 8 Summary comparing different types of electrolysers

Name	PEM Electrolyser	Alkaline Electrolyser	Solid Oxide Electrolyser
Electrolyte	Solid Polymer	Aqueous Alkaline Solution (KOH or NaOH)	Solid Oxide, Yttria-stabilised Zirconium Oxide
Electrical efficiency (based on lower heating value)	56-60%	63-70%	74-81%
Current Density [A/m²]	10,000-20,000	2,000-4,000	3,500-5,500
Operating Temperature [°C]	50-80	60-90	500-850
Input Component(s)	**Deionised Water**	**Deionised Water and** **Alkali Material**	Deionised Water (Steam)

Electrolysis will be essential in achieving maritime decarbonization goals, requiring:

- Scaling Up Infrastructure – Expanding electrolyzer capacity and integrating port-based hydrogen storage and bunkering facilities.

- Technological Advancements – Further R&D in PEM and SOEC to enhance efficiency and reduce costs.
- Regulatory Alignment – Standardizing hydrogen production, storage, and distribution to support cross-border maritime applications.

By linking renewable energy deployment with electrolysis capacity, ports and shipping sectors can secure a cost-effective, sustainable hydrogen supply, advancing the Joint Cross-Border Strategy's vision for a zero-emission maritime future.

Beyond electrolysis, several alternative pathways exist for producing green hydrogen. These include direct solar hydrogen production, biomass fermentation, and thermochemical biomass conversion. Each method offers distinct advantages and challenges, shaping its potential role in the transition to a zero-emission maritime sector.

Pathway 2 - Direct solar hydrogen production

This approach uses sunlight to split water into hydrogen and oxygen without relying on solar electricity generation or electrolysis. Three primary processes are under development:

- Photo-electrolysis utilizes a photoelectrochemical cell to drive water-splitting reactions. This technology, still in the research phase, shows promise in high-solar-irradiation regions, with efficiencies estimated at 10% (Grimm et al., 2020).
- Thermolysis involves heating water to high temperatures for decomposition. Modified thermochemical cycles reduce the required temperature from 2,500°C to 500–1,600°C, achieving energy efficiencies of 20–45% (Nikolaidis & Poullikkas, 2017). Solar heat collectors can enhance efficiency.
- Biophotolysis employs bacteria or algae to split water using sunlight. Although demonstrated in laboratory settings, challenges such as low efficiency (3–16%), the need for large surface areas, and high costs limit large-scale application (Melitos et al., 2021).

While these technologies remain pre-commercial, continued research could lead to scalable, cost-effective solutions for direct solar hydrogen production.

Pathway 3 - Biomass fermentation

Biomass fermentation uses bacteria to convert organic materials into hydrogen and CO_2, offering a low-energy alternative to thermochemical processes. It comprises:

- Dark Fermentation, an anaerobic process, decomposes biomass into hydrogen and CO_2, but current hydrogen yields remain low (40–60%). Combining it with photo-fermentation or microbial fuel cells may enhance efficiency (60–80%) (Ghavam et al., 2021).
- Photo-Fermentation relies on photosynthetic bacteria to convert organic acids into hydrogen and CO_2 under sunlight. While it offers potential, low solar-energy conversion (~0.1%) and the requirement for large reactor spaces present significant barriers (Nikolaidis & Poullikkas, 2017).

- Multi-Stage Fermentation integrates dark and photo-fermentation, improving hydrogen output while reducing energy demands. Higher operating temperatures may increase efficiency and scalability.

Although biomass fermentation is less energy-intensive than thermochemical methods, its lower hydrogen yield remains a challenge.

Pathway 4 - Thermochemical biomass conversion

This method uses heat to break down biomass into hydrogen-rich gases and includes two primary processes:

- Pyrolysis thermally decomposes biomass at 380–530°C in the absence of oxygen, producing hydrogen, carbon monoxide, biochar, and hydrocarbons. Energy efficiency ranges from 35–50% depending on feedstock type and operating conditions (Nikolaidis & Poullikkas, 2017).
- Gasification converts biomass into syngas (hydrogen and carbon monoxide) at 500–1,400°C. Hydrogen yield can be enhanced through steam reforming and water-gas shift reactions, achieving efficiencies of 52%. Supercritical water gasification is an emerging variant for wet biomass, with carbon-conversion efficiencies of 80–100% (Yakaboylu et al., 2015).

While gasification has been commercially demonstrated, large-scale deployment is still limited.

These alternative hydrogen production pathways present long-term potential but require further technological advancements before achieving widespread adoption. To integrate these technologies effectively into the maritime sector, the following strategic considerations must be addressed:

- Scaling R&D Investments – Encouraging innovation in direct solar hydrogen and biomass-based production.
- Infrastructure Development – Establishing pilot projects in ports to assess feasibility and scalability.
- Regulatory Adaptation – Creating standardized policies for biomass and solar-based hydrogen integration into maritime transport.
- Cross-Sector Collaboration – Strengthening partnerships between ports, research institutions, and energy providers to accelerate market readiness.

While electrolysis remains the most immediate and scalable solution, alternative pathways provide long-term diversification in hydrogen supply, supporting a resilient, decarbonized maritime industry.

4.1.4 Level of Maturity of Technologies

The development and deployment of **hydrogen production technologies** are at varying stages of maturity, influencing their feasibility for large-scale implementation in the maritime sector. According to scientific literature and market data, the most mature technologies for green hydrogen production are alkaline and proton exchange membrane (PEM) electrolysers. Alkaline electrolysers have been fully proven in operational environments, while PEM electrolysers are close to full-scale deployment. These technologies are currently the most viable options for integrating hydrogen into maritime applications.

Conversely, solid oxide electrolysis cells (SOECs), despite their potential for higher efficiency, remain at the early research stage, with limited testing in industrial environments. Other hydrogen production pathways, including direct solar hydrogen production, biomass fermentation, and thermochemical biomass conversion, have not yet reached commercial readiness. Among these, thermal gasification and pyrolysis have progressed further, with some demonstration-scale implementations, but still require further optimization before full commercialization.

The technology readiness levels (TRLs) of these hydrogen production technologies are summarized in Table 10, which provides an overview of their current development status. While electrolysis remains the dominant approach, ongoing research into alternative methods such as photo-electrolysis, thermolysis, and biophotolysis could expand the range of hydrogen production options in the future.

Table 9 TRL of green hydrogen-production technologies

Production pathway	**Technologies**	**Remarks**	**Technology readiness level (TRL)**	**Sources**
1. Electrolysis	Alkaline electrolyser	Alternative technologies to split pure water into hydrogen and oxygen using electricity	9	(Rouwenhorst, Van der Ham, Mul, & Kersten, 2019), (Smith, Hill, & Torrente-Murciano, 2020)
	PEM electrolyser		8-9	(Smith, Hill, & Torrente- Murciano, 2020)
	SOEC electrolyser		3-5	(Rouwenhorst, Van der Ham, Mul, & Kersten, 2019), (Smith, Hill, & Torrente-Murciano, 2020)

2. Direct solar hydrogen production	Photo-electrolysis	Direct production from water using solar energy, without using electrolysis	1-3	(Smith, Hill, & Torrente- Murciano, 2020)
	Thermolysis		3-4	(Parkinson, 2019)
	Biophotolysis		1-3	(Smith, Hill, & Torrente- Murciano, 2020)
3. Biomass **fermentation**	Dark fermentation	Biochemical process, using bacteria.	4	(LBST and Hinicio, 2015)
	Photo-fermentation		1-3	Concluded from Nikolaidis & Poullikkas (2017)
4 Thermochemical biomass conversion	Pyrolysis	Thermochemical decomposition of biomass.	6	Concluded from Papadokonstantakis (2019)
	Thermal gasification		5-8	(LBST and Hinicio,
	Supercritical water gasification		4	2015), (Parkinson, 2019)

Note: TRL 1 = Basic principles observed; TRL 2 = Concept formulated; TRL 3 = Experimental proof of concept; TRL 4 = Validated in lab; TRL 5 = Validated in relevant environment; TRL 6 = Demonstrated in relevant environment; TRL 7 = System prototype demonstration in operational environment; TRL 8 = System complete and qualified; TRL 9 = System proven in operational environment.

The transition to **hydrogen-powered vessels** is also in its early stages. The maritime industry has only recently begun testing and operating hydrogen-powered engines and fuel cell systems. One of the first projects, led by Sandia National Laboratories in 2016, involved a small passenger ferry powered by a hydrogen fuel cell system operating in San Francisco Bay. Since then, five demonstration vessels have successfully sailed, and multiple shipping consortia have launched projects aimed at introducing hydrogen-powered vessels into regular service by 2023/2024. These ongoing developments indicate a growing commitment to hydrogen as a clean maritime fuel, although significant technological, regulatory, and infrastructure advancements are still required for full-scale adoption.

The maritime sector must continue to monitor technological progress, invest in pilot projects, and collaborate on regulatory frameworks to support the transition toward hydrogen-powered shipping. By leveraging the most mature technologies while fostering innovation in emerging pathways, the industry can accelerate the decarbonization of maritime transport and align with the broader EU goals for a sustainable, zero-emission economy.

4.1.5 Developments in the Production Capacity of Green Hydrogen

Global hydrogen production in 2021 reached 94 million tonnes (Mt), with the vast majority classified as grey hydrogen, primarily used in refineries and fertilizer production (IEA, 2022). By comparison, international shipping consumes approximately 285 Mt of conventional residual and distillate fuels annually, which is equivalent to around 95 Mt of hydrogen when considering its lower heating value. This highlights the scale of hydrogen demand that would be required for a full transition to hydrogen-based maritime fuels.

Despite the current limitations, the production capacity for green hydrogen—generated through electrolysis using renewable energy—is expanding rapidly. As of 2021, the global electrolyser capacity dedicated to green hydrogen production was only 0.3 GW, a relatively small figure compared to future projections. However, announced expansion plans suggest that global capacity could reach 260 GW in the coming years (IEA, 2021). This surge in capacity is supported by 460 electrolyser projects under development, with approximately 175 already under construction or having passed final investment decisions.

A key trend in the sector is the rapid increase in electrolyser unit size, which is expected to grow significantly over the next decade. While the average electrolyser size in 2021 was only 5 MW, projections suggest this could rise to 260 MW by 2025 and reach 1 GW by 2030 (IEA, 2022). This scaling-up of electrolyser technology will play a critical role in enabling green hydrogen to become a viable alternative to fossil fuels in various sectors, including heavy industry, transportation, and maritime applications.

Beyond energy production and industrial applications, hydrogen is also being explored as a flexible energy carrier for power generation during periods of low renewable energy availability, such as cloudy or windless conditions. Additionally, hydrogen-based fuels could serve as an essential component in decarbonizing heavy-duty transport and shipping, as well as in the manufacturing of green cement and green steel.

A non-exhaustive list of large green hydrogen projects worldwide is presented in Table 11, illustrating the growing global commitment to increasing green hydrogen production capacity through electrolysis. These projects reflect a strategic push by governments and industries to scale up renewable hydrogen infrastructure, addressing the need for sustainable fuel alternatives in both land-based and maritime applications.

This rapid expansion of green hydrogen production capacity will be crucial in supporting the transition to zero-emission shipping, as well as in meeting the broader European and international climate targets. However, continued technological advancements, investment, and policy support will be essential to ensuring cost reductions, efficiency improvements, and infrastructure readiness for large-scale hydrogen adoption in the maritime sector.

Table 10 Large green hydrogen projects worldwide

Project	Stakeholders	Country	Electrolyser capacity	Hydrogen production volume (kt/year)	Project stage	Start of operation (year)	Remarks
Pampas plant (IEA, 2022) **(Politi, 2021)**	Fortescue Future Industries	Argentina	15 GW	2,250	Announced	2030 (start of export in 2024)	Patagonian Rio Negro province. Use of wind energy.
Asia Renewable Energy Hub (FuelCellsWorks, 2022) **(HyResource, 2022)**	NW Interconnected Power Pty Ltd.	Australia	14 GW	1,600	Under development	2027-2028	
Western Green Energy Hub (FuelCellsWorks, 2022) **(HyResource, 2022)**	InterContinental Energy, CWP Global, Mining Green Energy Ltd.	Australia	28 GW	Over 3,000	Under development	2028	

HyEnergy Project (Province Resources Limited, 2022) (HyResource, 2022) **(Statista, 2021)**	Total Eren, Province Resources Ltd.	Australia	8 GW	550	Announced	Unknown In a document from Province Resources Ltd, a completion in Q1 2023 is mentioned.
Murchison Hydrogen Renewables Project **(Statista, 2021) (HyResource, 2022)**	Murchison Hydrogen Renewables Pty Ltd. (Parent company: Copenhagen Infrastructure Partners)	Australia	5 GW	Unknown	Announced	Unknown

Pacific Solar Hydrogen (Austrom Hydrogen, sd)	Austrom Hydrogen	Australia	3.6 GW	200	Announced	2025- 2030	Construction is planned for 2024 and should run at full capacity in 2030.
H2-Hub Gladstone (Queensland Government, 2022) **(HyResource, 2022)**	The Hydrogen Utility	Australia	3 GW	Unknown	Announced	2023	Up to 5,000 tonnes per day in ammonia will be produced from the hydrogen.
Unnamed (Geraldton) (Wong, 2022)	BP	Australia	Unknown	Unknown	Announced	Unknown	1 million tonnes/yr of green ammonia, based on 4 GW wind/solar generation capacity.

Project	Stakeholders	Country	Electrolyser capacity	Hydrogen production volume (kt/year)	Project stage	tart of operation (year)	Remarks
Base One (Collins L. , 2020)	Enegix Energy, Enerwind, Black & Veatch, Ceará state government	Brazil	Not stated	600	Announced	2025	Use of 3.4 GW of combined baseload wind and solar power.
HyEx (Djunisic, 2022)	Engie Latam SA, Enaex SA	Chile	0.026 GW	Unknown	Announced	2024	Enaex proposed to build a green ammonia plant with a capacity of 18,000 t/year, using Engie's green hydrogen.
HNH (Collins L. , 2020)	AustriaEnergy, Ökowind EE, CIP	Chile	1.4 GW	150-175 (800-1,000 kton NH3)	Announced	2026	1.8 to 2 GW of onshore wind power, Haber-Bosch ammonia production.

Sinopec Xinjiang Kuqa green hydrogen pilot project (Balkan Green Energy News, 2022) **(NS Energy Business, 2021)**	Sinopec, China Petroleum	China	0.3 GW	20	Under development (started in Dec. 2021)	2023	
Beijing Jingneng Inner Mongolia (Collins L. , 2020) (Brown & Grünberg, 2022)	Beijing Jingneng	China	< 5 GW	400-500	Under construction	Before 2025	Use of onshore wind and solar.
Unnamed (Greater Copenhagen) (S&P Global, 2021) **(World-Energy, 2020)**	Orsted, A P MollerMaersk, DSV Panalpina, DFDS, SAS and Copenhagen Airports	Denmark	1.3 GW	250	Announced (feasibility study underway)	2023	First phase 2023: 10MW electrolyszer. By 2027: 250 MW. By 2030: 1.3 GW.

Unnamed (Collins L. , 2020) (State of Green, 2021)	CIP, Moller- Maersk, DFDS, Arla, Danish Crown, DLG	Denmark	1 GW	160 (900 kton NH3)	Under development	2025-2027	Located in Esjberg. The intended final product is green ammonia for fertiliser production and shipping.
Unnamed (H2 Energy Europe, 2021)	H2 Energy Europe	Denmark	1 GW	90	Under development	2024 (earliest)	Located in Esjberg. The hydrogen will be used as a truck fuel.
Fortescue project (PV Magazine, 2022) (Scully, 2022)	Fortescue Future Industries, Egyptian Government	Egypt	3.6 GW	500	Announced	Unknown	Plans to develop a 9.2 GW wind and solar facility.

Project	Stakeholders	Country	Electrolyser capacity	Hydrogen production volume (kt/year)	Project stage	Start of operation (year)	**Remarks**
HyDeal Ambition (McPhy, 2021)	DH2/Dhamma Energy, McPhy Energy, Enagás, Gazel Energie, Cube, EIB, among others	Europe (Spain, France, Germany)	67 GW	3,600	Under development	2022-2030	Includes various market players and locations in Europe. The production of green hydrogen in Spain is planned to start in 2025.
AquaVentus (FuelCellsWorks, 2022) **(AquaVentus, 2022)**	Consortium incl. RWE, Vattenfall, Shell, E.ON, Siemens Energy, Vestas	Germany	10 GW	1,000	Announced	2025	Planning to generate at full capacity in 2035.

HyTech Hafen Rostock (RWE, sd)	Rostock EnergyPort cooperation GmbH, RWE Generation, EnBW Neue Energien GmbH, RheinEnergie AG and Rostock Port GmbH	Germany	0.1 GW	6.5	Announced	2026	
White Dragon (Collins L. , 2020) **(Polychroniou, 2022)**	Among others: DEPA, DESFA, Hellenic Petroleum, Terna Energy, Damco Energy	Greece	5 GW	283	Announced	2029	Use of solar power.

Unnamed (Collins L. , 2020)	EI-H2, Zenith Energy	Ireland	< 3.2 GW	240 (own estimate)	Feasibility study	2028	Use of 3.2 GW of offshore wind. A 500 MW green ammonia facility is planned.
Reckaz (FuelCellsWorks, 2022) **(Rec-kaz, 2021)**	SVEVIND group, ILF Consulting Engineers, Kazakh Government	Kazakhstan	30 GW	3,000	Announced	2028	At the end of 2021, a concept study for this facility was announced. Since then, no further news has been posted on the project website.
Aman (FuelCellsWorks, 2022) (Hollands, 2022)	Mauritania government, CWP Global	Mauritania	16-20 GW	1,700	Announced	Unknown	Unknown when it will start, but next steps in this project have been announced.

Project	Stakeholders	Country	Electrolyser capacity	Hydrogen production volume (kt/year)	Project stage	Start of operation (year)	Remarks
Nour Project (IEA, 2022) **(Collins L. , 2021)**	Chariot	Mauritania	10 GW	1,730	MoU signed	Unknown	Offshore wind and solar power in desert regions.
Beijing Jingneng Inner Mongolia (Statista, 2021) (Brown & Grünberg, 2022) (World-Energy, 2020)	Beijing Jingneng Clean Energy Co.	Mongolia	5 GW	400	Under constructio n	Unknown (2021 was planned)	
NorthH2 (FuelCellsWorks, 2022)	Groningen Seaports, Eneco, RWE, Equinor, Shell, Gasunie, OCI, Province of Groningen				Announced (Feasibility studies underway)		Planning to generate at full capacity

(NorthH2, 2022)		Netherlands	>10 GW	1,000		2027	in 2040.
SeaH2Land (Collins L. , 2020)	Orsted, ArcelorMittal, Yara, Dow Benelux, Zeeland Refinery	Netherlands and Belgium	1 GW	Not stated	Announced	2030	Use of a 2-GW offshore wind farm in the Dutch North Sea.
Green Energy Oman (FuelCellsWorks, 2022) **(OQ, 2022)**	OQ (Oman Oil Company), InterContinental Energy and EnerTech	Oman	14 GW	1,800	Announced	2038	
	Axelera, Bondalti, CEA, DLR< EDP, Efacec, ENGIE, Galp, ISQ,						Located at the port of Sines. Start of construction

GreenH2Atlantic (Green H2 Atlantic, 2022) **(ENGIE, 2021)**	Inesctec, Martifer Group, McPhy and Vestas	Portugal	0.1 GW	10	Announced	2025	planned in 2023 and completion expected in 2025.
MadoquaPower 2X (Klevstrand, 2022)	CIP, Madoqua Renewables, Power2X	Portugal	0.5 GW	50 + 90 (500 kton NH3)	Announced	Not stated	Located at the port of Sines.
Unnamed (Klevstrand, 2022)	NeoGreen, Frequent Summer	Portugal	> 0.5	Not stated	Announced	Not stated	Located at the port of Sines.
H2 Sines (Collins L. , 2020)	EDP, Galp, Martifer, REN, Vestas	Portugal	1 GW	Not stated	Feasibility study	2030	Located at the port of Sines.
Neom Green Hydrogen	NEOM, Air Products,	Saudi Arabia	4 GW	Unknown	Under developmen	2026	1.2 million tonnes of green ammonia are produced from the

Project	Stakeholders	Country	Electrolyser capacity	Hydrogen production volume (kt/year)	Project stage	Start of operation (year)	Remarks
Project (ACWA Power, 2022) (FuelCellsWorks, 2022)	ACWA Power, ThussenKrupp				t (started in May 2022)		hydrogen to transport overseas.
Hydrogen City Project (Collins L. , 2022)	Green Hydrogen International, SpaceX	United States	60 GW	2,500	Announced	2026 (first 2 GW phase)	

Note: This table provides a non-exhaustive overview

4.2. Hydrogen Storage Technologies

Hydrogen storage technologies vary significantly in maturity, scalability, and practical application (Figure 11). The choice of storage method directly impacts the feasibility of hydrogen adoption in long-haul transport, maritime applications, and cross-border energy trade, key pillars of an effective overseas strategy.

Compressed hydrogen (CH_2) (TRL 8/9) is among the most mature storage solutions. However, its low volumetric density (~40 kg/m³ at 700 bar) and the weight of composite storage tanks pose challenges, particularly for large-scale transport and maritime applications, where space and weight optimization are crucial.

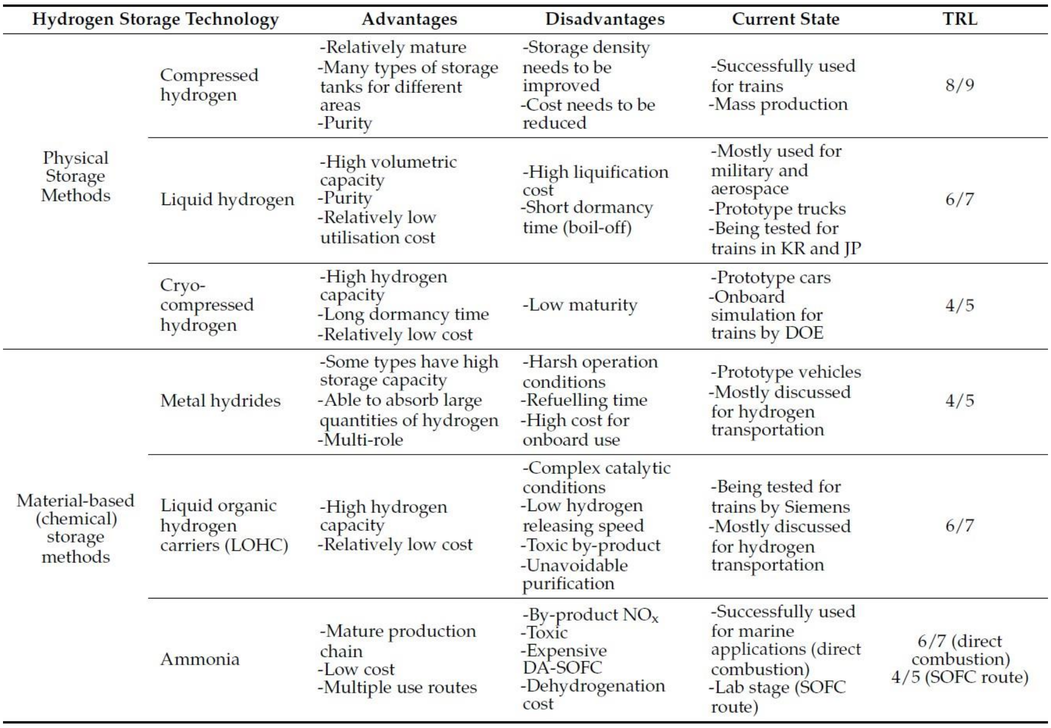
Liquid hydrogen (LH_2) (TRL 7/8) offers higher density (71 kg/m³), making it suitable for compact storage in aviation, shipping, and remote energy hubs. However, its reliance on cryogenic liquefaction (-253°C) leads to high energy consumption (30–40% of hydrogen's initial energy content) and operational challenges, such as boil-off losses and complex insulation requirements. This limits its cost-effectiveness for long-term overseas transport unless supported by advanced cryogenic infrastructure.

Cryo-compressed hydrogen (CcH_2) (TRL 4/5) combines cryogenic cooling with moderate pressures (below 700 bar), improving storage density and energy efficiency. While promising, scalability, cost, and infrastructure gaps remain significant barriers to deployment, particularly in maritime and long-haul transport networks.

Material-based storage solutions—such as ammonia, methanol, liquid organic hydrogen carriers (LOHC), and metal hydrides—offer alternative low-pressure, high-density storage pathways. LOHC systems (TRL 5/6) and metal hydrides (TRL 3/4 for large-scale applications) allow hydrogen to be chemically bound, easing transport and storage. However, energy-intensive extraction processes remain a limitation, especially for maritime fuel cells, where high-purity hydrogen is required.

While CH_2 and LH_2 are the most deployable options, CcH_2 and material-based solutions could overcome logistical and economic challenges for hydrogen storage in overseas transport corridors, remote regions, and large-scale energy hubs. Their development, along with advancements in infrastructure, insulation, and material science, will be essential for integrating hydrogen as a viable global fuel.

Figure 10 Summary of different hydrogen storage technologies



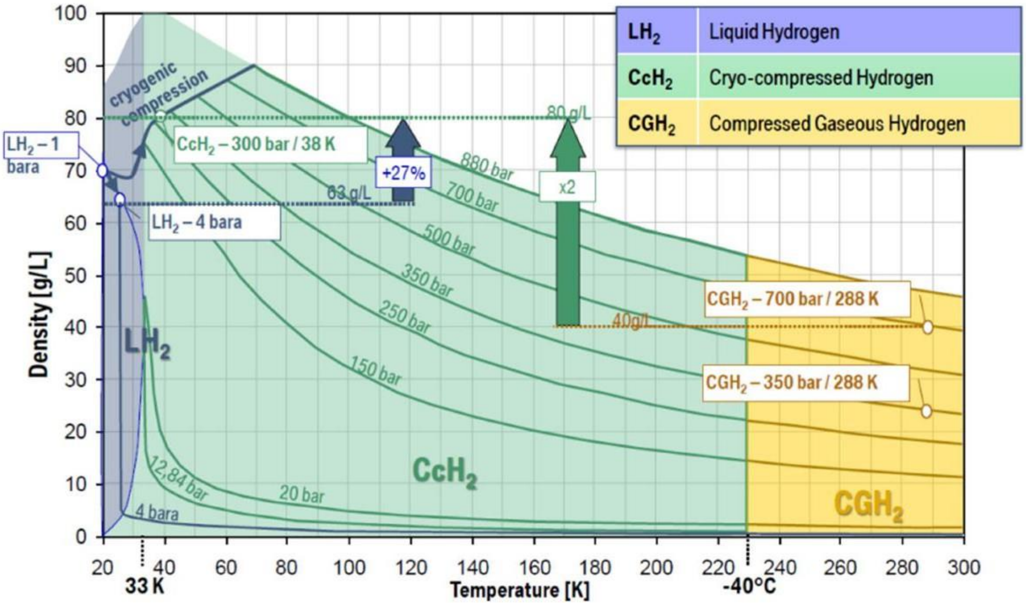
Hydrogen Storage Technology		Advantages	Disadvantages	Current State	TRL
Physical Storage Methods	Compressed hydrogen	-Relatively mature -Many types of storage tanks for different areas -Purity	-Storage density needs to be improved -Cost needs to be reduced	-Successfully used for trains -Mass production	8/9
	Liquid hydrogen	-High volumetric capacity -Purity -Relatively low utilisation cost	-High liquification cost -Short dormancy time (boil-off)	-Mostly used for military and aerospace -Prototype trucks -Being tested for trains in KR and JP	6/7
	Cryo-compressed hydrogen	-High hydrogen capacity -Long dormancy time -Relatively low cost	-Low maturity	-Prototype cars -Onboard simulation for trains by DOE	4/5
Material-based (chemical) storage methods	Metal hydrides	-Some types have high storage capacity -Able to absorb large quantities of hydrogen -Multi-role	-Harsh operation conditions -Refuelling time -High cost for onboard use	-Prototype vehicles -Mostly discussed for hydrogen transportation	4/5
	Liquid organic hydrogen carriers (LOHC)	-High hydrogen capacity -Relatively low cost	-Complex catalytic conditions -Low hydrogen releasing speed -Toxic by-product -Unavoidable purification	-Being tested for trains by Siemens -Mostly discussed for hydrogen transportation	6/7
	Ammonia	-Mature production chain -Low cost -Multiple use routes	-By-product NO_x -Toxic -Expensive DA-SOFC -Dehydrogenation cost	-Successfully used for marine applications (direct combustion) -Lab stage (SOFC route)	6/7 (direct combustion) 4/5 (SOFC route)

Figure 12 illustrates the relationship between hydrogen density, pressure, and temperature, providing key insights into hydrogen's physical properties under different conditions. As pressure increases, hydrogen becomes more compact, allowing for higher storage density, which is crucial for its use as a fuel in maritime transport, aviation, and energy applications.

At lower temperatures, particularly in cryogenic conditions, hydrogen reaches its liquid state, significantly increasing its energy density per unit volume. This is essential for efficient transport and storage, as liquid hydrogen (LH_2) occupies far less space compared to its gaseous form at ambient temperatures.

The figure helps illustrate the trade-offs between high-pressure gas storage and cryogenic liquid storage, both of which play a vital role in the development of hydrogen-powered fuel cells, bunkering infrastructure, and zero-emission transport solutions.

Figure 11 Hydrogen density versus pressure and temperature



4.2.1 Hydrogen Integration on Board Ships

The first hydrogen-powered vessel demonstrators have introduced fuel cell systems with limited power and storage capacities in the range of hundreds of kilograms of hydrogen. While these early-stage projects remain small in scale, they have successfully demonstrated the technical feasibility of hydrogen propulsion in maritime transport. However, to align with the common cross-border strategy for green shipping, efforts must now focus on scaling up hydrogen vessel deployment and developing the necessary infrastructure and regulatory frameworks to enable large-scale commercial use.

Currently, three notable vessels represent significant advancements in hydrogen maritime applications:

- SUISO FRONTIER – A hydrogen carrier with a cargo capacity of 1,250 m³ in vacuum-insulated LH$_2$ tanks. However, it still operates on traditional diesel-electric propulsion, underscoring the current transition phase in maritime hydrogen adoption.
- MF HYDRA – A fully hydrogen-powered ferry operating in Norway, equipped with a PEM fuel cell system and a 4-ton LH$_2$ tank on the open deck. This vessel serves as a demonstration of hydrogen's potential in short-sea and regional passenger transport.
- ULSTEIN SX190 – An offshore support vessel integrating a 2 MW fuel cell stack, providing 4–5 days of autonomy in dynamic positioning (DP) mode. It showcases hydrogen's role in decarbonizing offshore operations.

Only recently has the maritime industry begun testing and deploying hydrogen-powered engines and fuel cell systems. The first pilot project, developed by Sandia National Laboratories (2016), introduced a hydrogen-powered passenger ferry in San Francisco Bay.

Today, at least five hydrogen-powered demonstration vessels have been launched, and several cross-border industry consortia are actively developing projects aimed at scaling hydrogen-powered shipping. To align with the cross-border greening strategy, coordinated efforts must focus on:

- Infrastructure Development – Establishing hydrogen bunkering facilities at key cross-border ports to support vessel deployment.
- Regulatory Alignment – Developing harmonized safety standards and certification processes to facilitate cross-border hydrogen vessel operations.
- Operational Viability – Enhancing fuel cell system efficiency, LH_2 storage, and onboard integration to support longer voyages and diverse maritime applications.
- Scalability & Investment – Supporting joint public-private initiatives to accelerate hydrogen vessel commercialization and supply chain expansion.

Hydrogen-powered vessels represent a critical step toward zero-emission maritime transport, but their widespread adoption will depend on infrastructure expansion, regulatory cooperation, and investment in scalable technologies.

To our current knowledge, five hydrogen-powered demonstration vessels have sailed, and several shipping-related consortia have initiated projects that should lead to hydrogen-powered vessels entering service in 2024.

GOLDEN GATE ZERO EMISSION MARINE HYDROGEN FUEL CELL VESSEL	
	The Water-Go-Round, launched in 2021, is the US's first fuel cell vessel and the world's top commercial fuel cell ferry. Constructed by GGZEM and partners, it showcases a significant leap in maritime power dynamics, especially in storage and bunkering infrastructure. Equipped with 360kW Hydrogenics fuel cells and Li-ion batteries, and Hexagon Composites' hydrogen tanks, it can sail for up to two days without refueling. GGZEM's innovative bunkering system allows refueling anywhere with truck access, highlighting hydrogen's potential in maritime fuel.
Tech. spec: H2 242kg, 250 bar CH2, up to 2 days operation; 2x300 kW shaft motors; 100 kWh batteries boost power to achieve 22kn; abt. 21m Loa, aluminium hull, 84 pax	
HYDROVILLE BEHYDRO ENGINES AND CMB.TECH'S	
	Hydroville, developed by CMB Technologies, is the first certified passenger shuttle powered by hydrogen and diesel engine. It underwent rigorous risk analyses and certification by Lloyd's Register Group. With dimensions of 14m length, 4.2m beam, and 0.65m draft, it cruises at 22kt with a max speed of 27kt, weighing 12t with full load displacement at 14t. It features two hydrogen/fuel-powered internal combustion engines (H2ICED) generating 441kW. Hydrogen is supplied from 12 205l tanks at 200bar pressure, with backup diesel fuel tanks of 265l each. Primarily a test platform for hydrogen tech.
Tech. spec: The ferry incorporates two hydrogen/fuel-powered internal combustion engines (H2ICED), which produce a total shaft power of 441kW. The fuel is supplied from 12 205l hydrogen tanks of 200bar pressure and two diesel fuel tanks holding a backup fuel volume of 265l each.	
ULSTEIN'S SX190 ZERO EMISSION OFFSHORE SUPPORT VESSEL	

The ULSTEIN SX190 Zero Emission DP2 marks Ulstein's debut in hydrogen-powered offshore vessels, utilizing a Nedstack fuel cell power system for clean operations. With 2 MW contribution from Nedstack fuel cell stacks, out of a total 7.5 MW onboard power, the vessel stores hydrogen in pressurized containers managed by standard crane operations, enabling flexible refueling.

The PEM fuel cells in the SX190 Zero Emission design utilize hydrogen from containerized pressure vessels.

Tech. spec.: L 99 m, B 23.4 m, Deck area 1000-1200 sqm, T 6.0 m Accommodation 60-90 POB, Prop. thrusters 2 x 1,280 kW, Tunnel thrusters 2x 750 kW, Deck strength 10 t/m2.

LIQUID HYDROGEN CARRIES SUISO FRONTIER

The Suiso Frontier, launched in 2021 by HySTRA as part of the HESC project, is a liquid hydrogen carrier designed to transport liquefied hydrogen safely over long distances by sea. Featuring a 1,250 m3 vacuum-insulated, double-shell-structure tank manufactured at Harima Works, it serves as a technology demonstration for establishing an international hydrogen energy supply chain. The vessel's maiden voyage between Australia and Japan took place in February 2022.

Tech. spec: Loa 116.0 m, B 19.0 m, T 4.5 m, cargo tank capacity approximately 1250 m3, diesel electric propulsion, speed 13 kn, 25 persons capacity, Class NK.

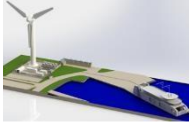
CFT AND NORLED "FLAGSHIP" HYDROGEN VESSEL

The FLAGSHIPS project, funded by a 5-million-euro EU grant, has delivered two zero-emission hydrogen fuel cell vessels in France and Norway.

In Lyon, CFT operates a hydrogen push-boat on the Rhône, while Norled operates the MF Hydra ferry in Stavanger, both entirely hydrogen-powered. Significant investments from CFT, Norled, and partners contributed to these vessels, aimed at advancing zero-emission waterborne transport.

Tech. spec.: The vessel is expected to bunker gaseous H2 daily between its six stops along the Judaberg- Helgoy route. Inboard PEM fuel cell will be supplied by Ballard Power System Europe.

DUAL PORTS PROJECT – FEASIBILITY OF HYDROGEN BUNKERING



ITM Power developed a modular and scalable bunkering system design adaptable to specific customer needs. The design was applied to the Orkney Islands, where the DUAL Ports hydrogen pilot is focused. Four options for hydrogen production and bunkering were considered based on electricity generation from wind, storage requirements, and electrolysis processes. Each scenario was fully specified and costed. The plant will be designed for general application in Europe (for the purpose of this study, it will be designed to CE standards).

Tech. spec.: The electrolyser will provide a peak output of 807 kg H2/day, falling to an expected 691kg/day at the end of life, produced by 3x stacks. The H2 purity is 99.999%. The electrolyser system will be packaged in a 30' ISO container for use outdoors and will deliver to a low pressure (20 bar) buffer tank.

4.2.2 Hydrogen Bunkering

Hydrogen bunkering is probably one of the less mature aspects of hydrogen technology. Referring to CH_2, several filling and refuelling stations already exist throughout the world. When it comes to LH_2, serious dearth of knowledge on the handling of cryogenic hydrogen in public areas for new distribution applications (e.g. truck refuelling or ship bunkering) exists. At the time being, the only LH_2 bunkering facility for ships is the one custom-designed for the MF HYDRA (Figure 5).

In the context of fixed H2 tanks integrated on board, hydrogen bunkering is no more avoidable by using swappable containment solutions. Hydrogen powered vessels need a fast and efficient refuelling procedure to increase their competitiveness, and this solution can only be provided by further developing hydrogen bunkering. The current bunkering rates for LH2 are in the order of hundreds of kgH2/h.

Figure 12 LH2 bunkering facility for ships, custom-designed for the MF HYDRA

4.3. Sustainability

In this section, the sustainability of green hydrogen production (using grey hydrogen as a reference to estimate GHG emissions reduction) and its use as a fuel in maritime ships is analyzed.

4.3.1 GHG Performance

Life-Cycle GHG Emissions of Hydrogen in Maritime Transport

Hydrogen is a zero-carbon fuel that does not generate direct greenhouse gas (GHG) emissions during combustion. However, the full life-cycle emissions of hydrogen depend on its production, storage, transport, and end-use technologies. To align with the Joint Cross-Border Strategy for Greening Maritime Routes, a comprehensive approach to GHG emissions is necessary, ensuring that hydrogen's integration into shipping results in meaningful decarbonization.

Hydrogen Combustion and Onboard Emissions

When used in internal combustion engines (ICEs), hydrogen-powered vessels may still emit small amounts of GHGs if a carbon-based pilot fuel is required. These emissions can be eliminated by switching to net-zero carbon fuels or avoided entirely with the use of fuel cells, which do not require combustion.

GHG Emissions from Hydrogen Production and Transportation

The GHG emissions of hydrogen depend primarily on how it is produced:

- Grey Hydrogen is produced from natural gas (steam methane reforming - SMR) with high associated CO_2 emissions.
- Blue Hydrogen follows the same production process but integrates carbon capture and storage (CCS) to reduce emissions.
- Green Hydrogen is produced via water electrolysis using renewable electricity, resulting in near-zero GHG emissions.

However, if electrolyzers operate on grid electricity, emissions will depend on the electricity mix used at the time of production. High-temperature electrolysis may also generate emissions if the heat input is not from renewable sources.

Hydrogen Storage, Transport, and GHG Implications

The method of hydrogen transport and storage also affects life-cycle emissions:

- Liquid Hydrogen (LH_2) requires cryogenic cooling to -253°C, consuming up to 30% of hydrogen's energy content for liquefaction. If renewable electricity is used, emissions are minimized. If grid or fossil-based electricity is used, emissions increase significantly. Reported emissions vary based on electricity source:
  - Wind-powered liquefaction: 4.6g CO_2 eq/MJ hydrogen
  - Solar-powered liquefaction: 11.7g CO_2 eq/MJ hydrogen
  - Grid-powered liquefaction: 43.3g CO_2 eq/MJ hydrogen
- Hydrogen Carriers (LOHC, Ammonia, Methanol) require conversion and reconversion processes, which can add GHG emissions, depending on energy sources used.
- Onboard Storage & Reforming: If carbon-based fuels (e.g., methanol, ammonia) are reformed onboard to produce hydrogen, CO_2 emissions occur. However, if pure hydrogen is bunkered, fuel cell-powered ships operate with zero direct emissions.

Lifecycle Approach to Hydrogen GHG Emissions

To ensure accurate accounting of hydrogen's true carbon footprint, lifecycle assessments must consider:

- Direct & Indirect Emissions: Including CO_2, CH_4, and N_2O, converted to CO_2-equivalents (CO_2-eq) using Global Warming Potential (GWP) factors.
- Emissions from Renewable Energy Infrastructure: The manufacturing and construction of wind turbines and solar panels introduce embedded emissions that must be distributed over their operational lifetime.
- Regulatory Frameworks: The IMO's Marine Fuel Life Cycle GHG Guidelines (MEPC.376(80)) include different hydrogen production pathways but do not yet color-code them (e.g., grey, blue, or green hydrogen). Regulatory alignment is needed to ensure transparent emissions reporting across borders.

The Lifecycle GHG emission factors for green hydrogen vs. fossil marine fuels is shown in the table 12.

Table 11 Lifecycle GHG emission factors for green hydrogen vs. fossil marine fuels

Fuel	Production pathway	GHG emission factor (g/MJ)	Source	Remarks
Grey hydrogen	Natural gas (SMR/ATR)	71-120	(Atilhan, et al., 2021) (Cetinkaya, Dincer, & Naterer, 2012) (Parkinson, 2019)	Upper and lower value from (Parkinson, 2019)
Blue hydrogen	Natural gas (SMR/ATR and CCS)	18-63	(Parkinson, 2019) (Atilhan, et al., 2021)	Lower value from (Atilhan, et al., 2021); higher value from (Parkinson, 2019).
Green hydrogen	Wind energy (electrolysis)	4-10		Lower value from (Parkinson, 2019); higher value from (Atilhan, et al., 2021).
	Solar energy (electrolysis)	9.3-30		Lower value from (Parkinson, 2019); higher value from (Atilhan, et al., 2021)
	Biomass (gasification)	2.1-61		Upper and lower value from (Parkinson, 2019)

VLSFO	-	92	(CE Delft, 2021) FuelEU Maritime proposal	Upstream emissions depend on crude oil source and refinery
MGO	**-**	**91**		

Note: SMR = steam methane reforming; ATR = autothermal reforming; CCS = carbon capture and storage; VLSFO = very low sulphur fuel oil; MGO = marine gasoil.

GHG Impact of Hydrogen Emissions in Maritime Transport

While hydrogen itself is a zero-carbon fuel, its emissions into the atmosphere have indirect greenhouse gas (GHG) effects, which must be considered in the Joint Cross-Border Strategy for Greening Maritime Routes. Unlike CO_2 or methane (CH_4), hydrogen's impact is not through direct radiative forcing but rather through its influence on atmospheric chemistry, particularly in relation to methane lifetime, tropospheric ozone formation, and stratospheric water vapor levels.

Indirect GHG Effects of Hydrogen Emissions

The Intergovernmental Panel on Climate Change (IPCC) acknowledges that hydrogen has an indirect climate impact but has yet to quantify its full global warming effect. Recent studies indicate that hydrogen leakage throughout the supply chain could offset some of the climate benefits if not properly controlled.

Hydrogen is the smallest and lightest molecule, making it prone to leakage from pipelines, storage tanks, and transport vessels. Leakage can also occur intentionally during start-up, shutdown, or purging of electrolysis systems. In worst-case scenarios, hydrogen losses may reach up to 9.2% of the volume produced. However, with proper capture and reuse, losses could be reduced to below 0.52%.

For liquid hydrogen (LH_2), the primary leakage mechanism is boil-off—the vaporization of hydrogen due to heat exposure. Boil-off rates (BOR) typically range from 0.1–5% per day, with an average of 1% per day. Onboard reliquefaction systems could help mitigate these losses, similar to the approach used in LNG carriers.

Hydrogen Emissions Across the Supply Chain

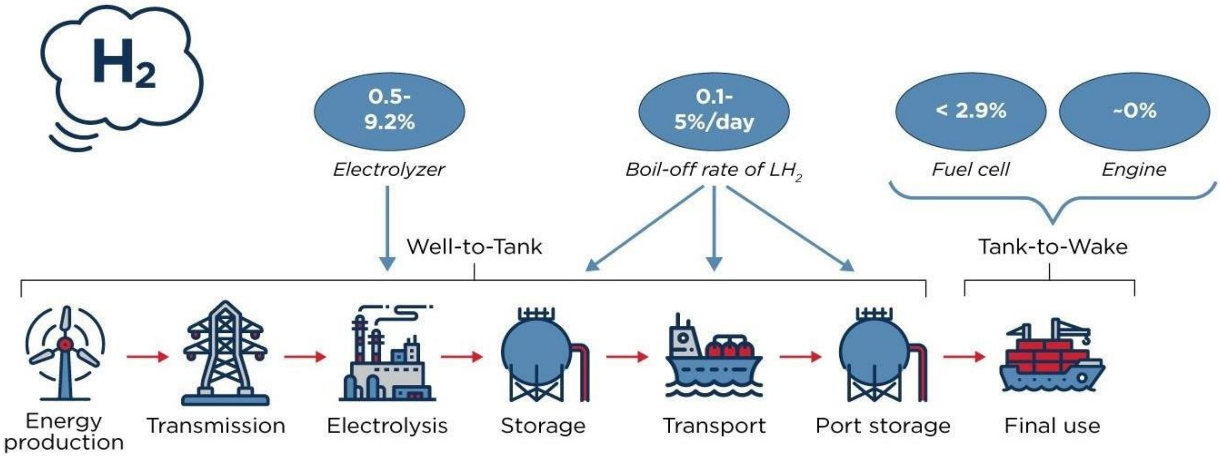
Throughout its supply chain, hydrogen can experience losses and emissions at various stages, depending on the technology and transportation method used. While advancements in containment and recovery systems continue to improve efficiency, some losses remain unavoidable.

- Electrolysis: Hydrogen venting and purging during production can lead to losses of up to 9.2% if not properly recovered. However, best-practice systems can minimize this to below 0.52%.

- Fuel Cells: Small amounts of hydrogen are lost through venting and purging, accounting for approximately 2.9% of total hydrogen consumption.
- Internal Combustion Engines (ICEs): Hydrogen emissions from combustion-based applications are considered negligible.
- Road Transport: Losses depend on the state of hydrogen storage. By 2030, losses are expected to reach 3% for gaseous hydrogen and 4–5% for liquefied hydrogen (Air Liquide estimate).
- Pipeline Transport: Hydrogen leakage through pipelines is projected to remain below 1% by 2030, according to the Joint Research Centre (JRC, 2022).

These figures highlight the importance of efficient hydrogen containment, advanced storage solutions, and technological improvements to minimize losses and ensure sustainability across the hydrogen supply chain.

Figure 13 Hydrogen emissions along the hydrogen supply chain, based on estimations from Frazer-Nash Consultancy (2022). This supply chain examines the import of hydrogen by ship in the form of liquid hydrogen (LH2).



Atmospheric Effects of Hydrogen Leakage

Hydrogen in the atmosphere interacts with hydroxyl radicals (OH), which play a crucial role in methane breakdown. Increased hydrogen concentrations reduce OH availability, extending the lifetime of methane, a potent greenhouse gas. This means that while hydrogen replaces fossil fuels (reducing direct CO_2 and CH_4 emissions), its leakage could indirectly increase methane's climate impact.

Additionally, hydrogen oxidation contributes to tropospheric ozone formation, another GHG. However, as fossil fuels are phased out, NO_x, CO, and VOCs emissions will decrease, offsetting some of this impact.

Hydrogen can also increase stratospheric water vapor, a known climate forcer. Recent research by Warwick et al. (2022) suggests that stratospheric water vapor contributes 30% of hydrogen's global warming potential (GWP).

Global Warming Potential (GWP) of Hydrogen

Hydrogen is often considered a clean energy carrier, but its potential impact on global warming is increasingly being studied. Unlike carbon dioxide (CO_2), hydrogen does not directly contribute to long-term warming. However, when released into the atmosphere, it influences chemical reactions that can indirectly increase methane and ozone levels, contributing to short-term climate effects.

Different studies have estimated the Global Warming Potential (GWP) of hydrogen over a 100-year time horizon (GWP100):

- Derwent et al. (2020): GWP100 = 5 ± 1, considering only effects in the troposphere.
- Field & Derwent (2021): GWP100 = 3.3 ± 1.4, suggesting a lower impact.
- Warwick et al. (2022): GWP100 = 11 ± 5, incorporating effects in both the troposphere and stratosphere, indicating a potentially higher influence.

For comparison, the GWP100 values of other greenhouse gases, as reported by the IPCC (2021), are:

- Carbon dioxide (CO_2) = 1 (baseline for all GWP calculations).
- Fossil methane (CH_4) = 29.8 ± 11.
- Non-fossil methane (CH_4) = 27.

While hydrogen's GWP remains significantly lower than methane, its atmospheric effects must be carefully managed to ensure that hydrogen leakage is minimized, particularly as the hydrogen economy scales up. The GHG impact of hydrogen emissions is summarized in Table 13.

Table 12 GHG impact of hydrogen emissions

Aspect	Value	Source	Remarks
Global warming potential of hydrogen over a period of 100 years (GWP_{100})	5 ± 1	Derwent et al. (2020)	Based on changes to the troposphere
	3.3 ± 1.4	Field & Derwent (2021)	Based on changes to the troposphere and stratosphere
	11 ± 5	Warwick et al (2022)	
Share of GHG emissions reduction that is offset by hydrogen leakage.	0.4% (assuming a H_2 leaking rate of 1%)	Warwick et al (2022)	In a scenario in which 40% of final fossil energy consumption is replaced by hydrogen.
	4% (assuming a H_2 leaking rate of 10%)		

Balancing Hydrogen's Climate Benefits with Leakage Risks

A study by Warwick et al. (2022) modeled a global hydrogen economy scenario where 40% of final fossil energy consumption is replaced by hydrogen. The impact of hydrogen leakage was assessed as follows:

- 1% hydrogen leakage: Offsets only 0.4% of total GHG reductions.
- 10% hydrogen leakage: Offsets 4% of total GHG reductions.

Based on the literature review, it is concluded that the switch to a hydrogen economy can be expected to lead to a net reduction in GHG emissions.

4.3.2 Air Pollution

The combustion of conventional fossil fuels in ships results in air pollutant emissions that negatively impact crew health, port communities, and marine ecosystems. The extent to which hydrogen-powered vessels reduce air pollution depends on the engine system, design features, and the amount and type of pilot fuel used. In alignment with the Joint Cross-Border Strategy for Greening Maritime Routes, hydrogen offers a viable pathway to significantly reducing maritime air pollution, particularly when used in fuel cells rather than internal combustion engines (ICEs).

Hydrogen Combustion in Internal Combustion Engines (ICEs)

When hydrogen is used in a marine internal combustion engine, emissions of sulfur dioxide (SO_2), carbon monoxide (CO), heavy metals, hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), and particulate matter (PM) are virtually eliminated. This is because hydrogen fuel does not contain carbon, sulfur, or other contaminants commonly found in conventional residual and distillate marine fuels.

However, some level of emissions may still occur due to the use of pilot fuel and lubricating oil in certain engine designs. Pilot fuel is required as an ignition source for hydrogen combustion in ICEs and typically consists of fossil diesel, e-diesel, or biodiesel, accounting for 1–3% of total fuel use (HyMethShip, 2019).

Another concern is the formation of nitrogen oxides (NO_x) during hydrogen combustion, a phenomenon also observed in fossil fuel combustion. NO_x emissions arise due to the high combustion temperatures of hydrogen, which can cause thermal oxidation of nitrogen in the air. However, these emissions can be minimized through optimized combustion control techniques, such as adjusting the air-fuel ratio, water injection, or exhaust gas recirculation (EGR).

An alternative approach to NO_x reduction is Selective Catalytic Reduction (SCR) aftertreatment, which can further lower emissions but increases system complexity and operational costs. McKinsey & Company (2021) reports that with proper combustion control and SCR treatment, NO_x emissions from hydrogen combustion engines become insignificant. Similarly, Lewis (2021) states that hydrogen-fueled internal combustion engines (ICEs) are likely to outperform heavy fuel oil (HFO) equivalents in terms of NO_x emissions.

It is important to note that NO_x emissions from international shipping are regulated under Annex VI, Regulation 13 of the MARPOL Convention, which sets emission control standards for marine engines (see subsection 3.2.2.2 for further details on air pollution regulations under MARPOL Annex VI).

Fuel Cells: A Zero-Emission Alternative

Hydrogen-powered fuel cells offer a superior solution for reducing air pollutant emissions compared to hydrogen ICEs. Unlike combustion engines, fuel cells do not produce incomplete combustion byproducts, making them significantly more efficient while eliminating the need for pilot fuel.

In fuel cell propulsion systems, emissions of NO_x, SO_x, and PM are completely eliminated when hydrogen is used as a fuel. However, in Molten Carbonate Fuel Cells (MCFCs), Phosphoric Acid Fuel Cells (PAFCs), Solid Oxide Fuel Cells (SOFCs), and High-Temperature Proton Exchange Membrane Fuel Cells (HT-PEMFCs), low levels of NO_x emissions may be generated if carbon-based fuels are used for internal reforming to produce hydrogen. When pure hydrogen is used, NO_x emissions do not occur (DNV GL, 2017).

A study by Sandia National Laboratories on a hydrogen fuel cell-powered high-speed passenger ferry found that using fuel cells with renewable hydrogen led to a 99.2% reduction in NO_x emissions and a 98.6% reduction in PM emissions compared to a conventional diesel-powered ferry (AccessScience, 2019).

Hydrogen's Role in Reducing Air Pollution from Shipping

Hydrogen, particularly when used in fuel cells, offers a clean alternative to fossil fuels, significantly reducing the air pollutant emissions associated with maritime transport. The extent of these benefits depends on the fuel production pathway, onboard energy conversion system, and emission control measures. However, the overall trend is clear: transitioning to hydrogen as a marine fuel, especially through fuel cells, will play a key role in achieving zero-emission shipping and aligning with international environmental regulations.

Hydrogen-powered vessels exhibit significantly lower emissions of gaseous and particulate pollutants compared to conventional fossil-fueled ships, making them a crucial enabler of the Joint Cross-Border Strategy for Greening Maritime Routes.

4.3.3 Other Environmental Impacts

The large-scale production and deployment of green hydrogen require significant infrastructure, including renewable electricity generation, electrolysis systems, fuel cells, and biomass-based pathways. While hydrogen is a key enabler of zero-emission maritime transport, its environmental footprint depends on how it is produced, transported, and utilized. The Joint Cross-Border Strategy for Greening Maritime Routes must therefore consider not only GHG emissions reductions but also the broader environmental impacts of hydrogen's supply chain.

Renewable Electricity Generation

The expansion of renewable energy infrastructure is essential for green hydrogen production, but it comes with its own environmental considerations. The land or sea surface area required varies significantly by geography, solar radiation levels, and wind speeds. Large-scale green hydrogen production will necessitate extensive deployment of solar and wind farms, which may impact biodiversity, ecosystems, and land use patterns.

To minimize environmental conflicts, solar parks and onshore wind farms should be strategically located in areas unsuitable for agriculture, such as arid regions (e.g., northern Chile, western Australia, northeast Brazil, northern Africa, parts of the U.S. and China). Offshore wind energy provides an alternative in regions with limited land availability, but its effects on marine ecosystems must be carefully managed.

Environmental Impacts of Wind Farms

Wind farms have a relatively low operational footprint but create environmental impacts at various lifecycle stages:

- Manufacturing: The production of wind turbine components generates environmental impacts, particularly from steel and fiberglass production. Recycling these materials at the end-of-life stage significantly reduces their impact.
- Copper Accumulation: Wind turbine generators contain copper, which can accumulate in soil, plants, and animals, potentially causing metabolic disturbances and inhibited plant growth.
- Wildlife Impact: Wind turbines can harm birds and bats, particularly through collisions and habitat displacement. The full ecological impact remains uncertain, but careful site selection can reduce risks.
- Noise and Human Health: Construction and operation noise may cause disturbances for wildlife and contribute to sleep disorders and mental health effects among local residents and workers.
- Marine Ecosystem Impact: Offshore wind farms can affect marine mammals, with reports of Minke whale strandings linked to underwater turbine noise.

Additionally, wind farms can alter local wind patterns, reducing kinetic energy in the atmosphere, potentially leading to localized climate effects similar to increased moisture evaporation (Chowdhury et al., 2022). However, research suggests these effects are relatively minor and spatially limited.

Environmental Considerations for Solar Parks

The environmental footprint of solar parks is primarily associated with the manufacturing, construction, and disposal of photovoltaic panels and associated technologies. Unlike wind farms, solar installations have lower operational impacts but can still alter local ecosystems and microclimates.

A UK-based study (Armstrong, Ostle, & Whitaker, 2016) found that photovoltaic arrays in species-rich grasslands influenced air and soil microclimates, plant diversity, and CO_2 fluxes. Key findings included:

- Seasonal cooling effects of up to 5.2°C under photovoltaic arrays.
- Reduced diurnal temperature variations, affecting local biodiversity.
- Lower photosynthesis rates in winter and spring under solar panels.

Optimizing solar farm design and management can minimize these environmental costs, while further research is needed to better understand their long-term ecological effects.

Environmental Impact of Electrolysers

Large-scale electrolysers play a key role in green hydrogen production, but their environmental impact depends on electricity sources, material use, and water consumption. A Life Cycle Assessment (LCA) study (Delpierre et al., 2021) compared alkaline and PEM electrolysers to steam methane reforming (SMR) for hydrogen production. Key findings:

- The electrolyser itself contributed only 10% to overall environmental impact, while 80% came from electricity generation.
- Wind-powered electrolysis performed better in most impact categories, but SMR had lower water and resource depletion impacts.
- Electrolysers require pure, deionized water, which may contribute to water scarcity if sourced from freshwater reserves.
- Seawater desalination is a potential solution but can cause ocean biodiversity loss due to brine discharge and seawater intake disruption (Ghavam et al., 2021).

Lifecycle Impacts of Fuel Cells

The environmental footprint of fuel cells is primarily linked to manufacturing, particularly the production of fuel cell stacks containing critical materials like platinum. A lifecycle analysis of 1 kW PEM fuel cells (Stropnik et al., 2019) found:

- Manufacturing contributes more to environmental impact than operation (in 8 of 11 impact categories).
- Platinum accounts for 60% of manufacturing-related environmental impacts.
- Recycling platinum can reduce manufacturing impact by 37.3% and total lifecycle impact by 23.7%.
- Acidification potential could be reduced by 70.7% if platinum recycling is optimized.
- Extending fuel cell lifespan reduces its overall environmental footprint.

Fuel cells also offer non-emission benefits, including lower noise pollution, making them an attractive option for marine applications (DNV GL, 2017).

Environmental Considerations for Biomass-Based Hydrogen Production

The environmental impact of biomass-derived hydrogen depends heavily on biomass cultivation and processing methods. Biomass gasification is currently the most technologically advanced pathway, but it carries risks related to feedstock contaminants, air and water emissions, and hazardous byproducts. Key concerns include:

- Fly ash, dust, and gaseous emissions during gasification.
- Water pollution from cooling and syngas cleaning processes.
- Phenolic and tarry contaminants in wastewater.
- Potential hazards such as fire, gas leaks, and CO poisoning (Barahmand & Eikeland, 2022).

Biomass pyrolysis likely presents similar risks, although limited data is available.

A dark fermentation case study using sewage sludge and wine vinasse found that marine eutrophication was the largest lifecycle impact, driven by fertilizer use in vineyards. Another study based on sugar beet molasses found high impacts in terrestrial acidification, eco-toxicity, and water consumption, emphasizing the need for sustainable feedstock sourcing (Camacho et al., 2022).

Environmental Impact of Direct Solar Hydrogen Production

Direct solar hydrogen production (photo-electrolysis and thermolysis) remains at an early stage of development, with limited data on its environmental effects. However, key concerns include:

- Mining and resource extraction for photoelectrochemical cells.
- High-temperature solar collectors require metal-intensive manufacturing.
- Potential environmental risks include erosion, terrestrial eco-toxicity, and water pollution.

4.4. Use of Hydrogen

Hydrogen has significant potential to decarbonize maritime transport, particularly in island connectivity, inland navigation, and port operations. As part of the Joint Cross-Border Strategy for Greening Maritime Routes, hydrogen can support clean energy transitions in the shipping sector, reducing GHG emissions, air pollution, and dependence on fossil fuels.

Hydrogen for Island Transport and Energy Independence

While Croatian islands are connected to the mainland via submarine power cables, ensuring energy self-sufficiency remains a challenge, particularly for smaller islands and remote settlements. Hydrogen can function as both an energy storage solution and a clean fuel for public island transport, ferries, and waterborne mobility services.

A key advantage of hydrogen lies in its capacity to store surplus renewable electricity, which can later be converted into power or used for vessel propulsion. This is especially relevant outside the tourist season, when energy demand declines but renewable generation remains high. Hydrogen-powered stationary ferries—which currently rely on diesel engines for onboard electricity while docked—could eliminate emissions and noise pollution, significantly improving port air quality.

Hydrogen in Inland Waterway Transport and EU Hydrogen Corridors

The Danube River plays a crucial role in regional and European inland waterway transport, particularly for passenger and cargo vessels. In recent years, the demand for river cruising has grown, making decarbonization of this sector a strategic priority. Hydrogen is particularly attractive in this context due to ongoing EU initiatives to develop hydrogen transport corridors, linking Southeast Europe with Western EU markets. These efforts position hydrogen as a preferred alternative to fossil fuels for river transport, offering both economic and environmental benefits.

Hydrogen for Cold Ironing in Ports

A major application of hydrogen in maritime transport is in cold ironing, the process of supplying shore-side electricity to docked vessels. This is particularly relevant for ports handling large cruise ships, such as Dubrovnik, Split, and Zadar, where ships currently rely on fossil-fuel-powered generators while moored. These generators produce high levels of greenhouse gases (GHGs), air pollutants, and noise, impacting both port operations and urban environments.

To decarbonize port operations, it is necessary to transition to renewable energy sources (RES) or hydrogen-based solutions. Hydrogen fuel cells offer a clean and silent alternative to fossil fuel generators, ensuring a reliable and emissions-free power supply for ships at berth. This would significantly reduce local air pollution, lower carbon emissions, and support the sustainability of Croatian ports.

Challenges and Considerations

The expansion of hydrogen infrastructure in maritime transport must address several challenges:

- Hydrogen Storage & Distribution – Ensuring an efficient bunkering network for hydrogen-powered vessels in ports and waterways.
- Land and Resource Availability – Large-scale hydrogen production requires wind and solar parks, which must be developed without disrupting agriculture or biodiversity.
- Infrastructure Investment – Developing hydrogen supply chains, including electrolyzers, fuel cells, and refueling stations, requires coordinated public-private investment.
- Regulatory Frameworks – Establishing clear emissions limits and safety standards for hydrogen applications in ports and shipping.

4.5. Conclusion

Hydrogen is emerging as a key fuel for the decarbonization of maritime transport, offering significant reductions in greenhouse gas (GHG) emissions and air pollutants. While current hydrogen production is largely fossil-based, transitioning to green hydrogen—produced through electrolysis, biomass conversion, or solar-based methods—is essential for achieving a climate-neutral maritime sector.

Among available production pathways, electrolysis (alkaline or PEM) and thermochemical biomass conversion (via gasification) are the most viable short-term solutions due to their higher technology readiness levels (TRLs) and efficiency. However, global green hydrogen production remains insufficient—currently less than 0.1 Mt per year, while international shipping alone requires approximately 95 Mt per year. This highlights the urgent need for large-scale investment in production capacity and infrastructure.

Table 13 Summary of green hydrogen production pathways

Production pathway	Technology	Energy efficiency	Technology readiness level (TRL)
1. Electrolysis	Alkaline electrolyser	63-70% *	**9**
	PEM electrolyser	56-60% *	**8-9**
	SOEC electrolyser	74-81% *	**3-5**
2. Direct solar hydrogen production	Photo-electrolysis	10% **	**1-3**
	Thermolysis	20-45% **	**3-4**
	Biophotolysis	3-16% **	**1-3**
3. Biomass fermentation	Dark fermentation	60-80% ***	**4**
	Photo-fermentation	0.1% **	**1-3**
4. Thermochemical biomass conversion	Pyrolysis	35-50% ***	**6**
	Thermal gasification	52% ***	**5-8**
	Supercritical water gasification	**80% ***	**4**

*: Electricity-to-hydrogen

**: Solar energy-to-hydrogen

***: Biomass-to-hydrogen

Hydrogen offers considerable environmental benefits, particularly in reducing lifecycle GHG emissions. In shipping applications, hydrogen combustion in internal combustion engines (ICEs) produces no CO_2, SO_2, CO, heavy metals, hydrocarbons, PAHs, or particulate matter (PM). However, thermal NO_x emissions can occur, although they can be minimized through combustion control and SCR aftertreatment. Hydrogen fuel cells offer an even cleaner alternative, eliminating NO_x, SO_x, and PM emissions entirely and providing higher energy efficiency than ICEs.

Table 8 below summarizes the level of lifecycle GHG and air-pollutant emissions generated by using hydrogen as a marine fuel and compares this to using fossil marine fuels.

Table 14 The level of lifecycle GHG and air-pollutant emissions generated by using hydrogen as a marine fuel

	HFO, MGO*	**LNG***	**Green hydrogen - combusted in engines**	**Green hydrogen – used in fuel cells**
Lifecycle GHG emissions				
N_2O	Present	Present	Not present	Not present
CH_4	Low	Present at Otto engines	Not present	Not present
CO_2	Present	Present	From manufacturing wind turbines and solar panels	From manufacturing wind turbines and solar panels
H_2 (indirect)	Not present	Not present	From venting, purging and boil-off	From venting, purging and boil-off
Air pollutant emissions				
SO_2 and metals	Present	Not present	Not present	Not present
Carbon monoxide and hydrocarbons	Present	Present or increased	Not present	Not present
VOCs and PAHs	Present	Reduced	Not present	Not present
NO_x	Needs SCR for Emission Control Area	Otto engines meet Emission Control Area without SCR	No significant NO_x emissions with SCR	Not present
Direct particulate matter	Present	Reduced	Not present	Not present

Notes: HFO = heavy fuel oil; LNG = liquefied natural gas; MGO = marine gas oil; SCR = selective catalytic reduction.

*: Adapted from (Ash & Scarbrough, 2019). Pilot fuel is not considered in this table.

While hydrogen's environmental advantages are clear, challenges remain in scaling its adoption in maritime transport. Storage and distribution are major barriers, as compressed hydrogen has low volumetric density, while liquid hydrogen (LH_2) requires energy-intensive cryogenic storage with boil-off losses of 1-5% per day. Alternative hydrogen carriers, such as ammonia and Liquid Organic Hydrogen Carriers (LOHCs), are being explored to reduce storage complexity and improve cost efficiency.

Hydrogen adoption is particularly promising for short-sea shipping, inland waterways, and port operations, where fuel availability and infrastructure constraints are more manageable. Specific applications include:

- Island transport, where surplus renewable energy can be stored and used for hydrogen-powered ferries.
- River transport, particularly along the Danube, which is being developed as part of the EU's hydrogen corridors.
- Cold ironing in ports, replacing fossil-fuel-powered generators with hydrogen fuel cells to reduce GHG emissions and noise pollution.

Despite its potential, hydrogen still faces technological, economic, and regulatory challenges. Hydrogen engines and fuel cells for maritime applications are in early stages of commercialization, with only a few manufacturers offering hydrogen-powered marine engines. Additionally, hydrogen bunkering infrastructure is currently limited, requiring significant investment. Furthermore, land and resource availability for renewable energy expansion poses challenges, as large-scale wind and solar projects could compete with agriculture and biodiversity conservation (McKinsey & Company, 2023).

Final Conclusion

Hydrogen represents a transformative opportunity for maritime transport decarbonization, offering zero-emission potential and significant reductions in air pollutants. While short-sea shipping, inland waterways, and port electrification are ideal starting points, broader adoption in ocean-going vessels will require overcoming storage, distribution, and infrastructure challenges.

To enable hydrogen's large-scale deployment, key actions must include:

- Expanding hydrogen production and bunkering infrastructure in strategic maritime hubs.
- Advancing hydrogen fuel cell and ICE technologies to improve efficiency, reliability, and scalability.
- Developing regulatory frameworks to support hydrogen safety, emissions control, and market incentives.
- Investing in alternative hydrogen carriers (e.g., ammonia, LOHCs) to simplify storage and transport.

By addressing these challenges, hydrogen can become a cornerstone of sustainable maritime transport, aligning with EU Green Deal objectives and the Joint Cross-Border Strategy for Greening Maritime Routes.

5. Regulatory and Policy Considerations

5.1. Regulations for EU Member States

The European Hydrogen Strategy and associated policies represent the cornerstone of the EU's commitment to achieving climate neutrality by 2050, as outlined in the European Green Deal. Hydrogen, as a clean and versatile energy carrier, is pivotal for decarbonizing hard-to-abate sectors such as maritime transport, heavy industry, and aviation. These policies collectively address the integration of hydrogen technologies into the EU's energy, transport, and industrial systems.

The **Fit-for-55 Package**, launched in 2021, emphasizes hydrogen's role in reducing greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. Key initiatives such as FuelEU Maritime promote renewable and low-carbon fuels in shipping, with specific targets for reducing the greenhouse gas intensity of energy used by ships. The inclusion of maritime transport in the EU Emissions Trading System (EU ETS) further incentivizes the adoption of hydrogen and other clean fuels by imposing financial penalties on emissions. Additionally, the Renewable Energy Directive II (RED II) and its proposed revision (RED III) set ambitious targets for renewable energy use in transport, including a specific focus on renewable fuels of non-biological origin (RFNBOs) like hydrogen and ammonia.

The **FuelEU Maritime Initiative** establishes a harmonized framework to increase the share of renewable and low-carbon fuels in maritime transport. The initiative mandates progressive reductions in the greenhouse gas intensity of ship energy use, targeting an 80% reduction by 2050. Renewable hydrogen, with its low emissions profile, is well-suited to meet these targets. To support the uptake of such fuels, the initiative also ensures their availability in EU ports and incentivizes infrastructure development, such as refueling stations and grid connections for docked ships.

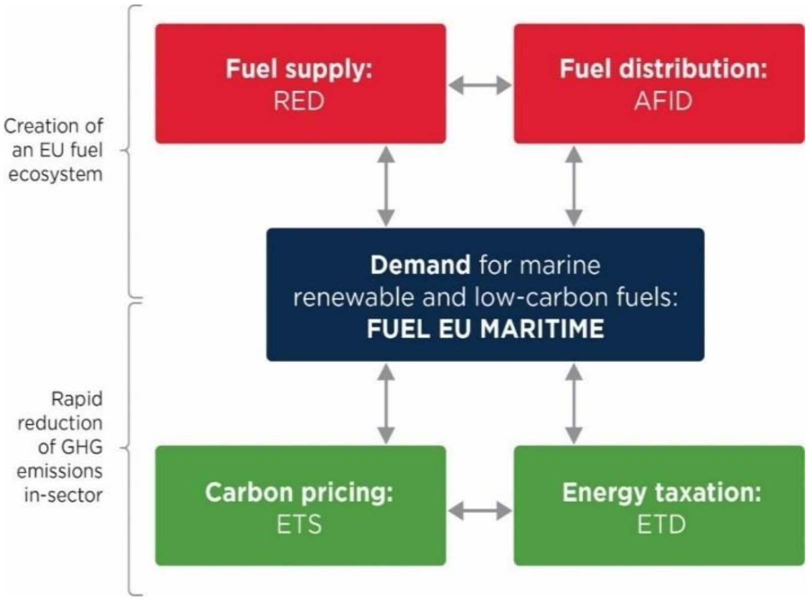
Complementing these measures, the **Energy Taxation Directive (ETD)** proposes taxing fuels based on their environmental impact, favoring cleaner alternatives like hydrogen. This revision aims to eliminate exemptions for high-polluting sectors such as maritime and aviation, driving a shift towards renewable energy.

The **Renewable Energy Directive (RED II)** and its proposed update (RED III) further reinforce hydrogen's integration into the energy system. By promoting renewable hydrogen through incentives and binding renewable energy targets, the directives aim to decarbonize transport and industry. A 2.6% sub-target for RFNBOs by 2030 highlights the focus on scaling up hydrogen technologies and ensuring their economic viability.

These initiatives are underpinned by the broader **Sustainable and Smart Mobility Strategy**, which targets a 90% reduction in transport emissions by 2050. Hydrogen-powered solutions are critical for achieving this goal, particularly in maritime and inland waterway transport. The strategy supports the development of hydrogen-compatible infrastructure and calls for increased investments in research, pilot projects, and the commercialization of hydrogen technologies.

Figure 14 The European Commission 'Fit-for-55' package

Figure 15 EU policies related to maritime transport



The European Hydrogen Strategy, launched on July 8, 2020, emphasizes hydrogen's pivotal role in achieving the European Green Deal's climate neutrality goals by 2050. Hydrogen is recognized as a clean energy carrier capable of replacing fossil fuels in hard-to-decarbonize sectors such as industry, long-haul transport, and maritime shipping. Current hydrogen production in the EU is mostly derived from fossil fuels, but the strategy aims to transition to renewable hydrogen produced via electrolysis powered by renewable energy sources. This transition is critical for reducing greenhouse gas emissions and supporting sustainable energy systems.

The strategy outlines a phased approach to hydrogen adoption. By 2024, the focus is on deploying renewable-powered electrolysers to decarbonize existing hydrogen production and foster new applications. Between 2024 and 2030, hydrogen will integrate into the energy system, supporting renewable energy storage and wider industrial use. Post-2030, hydrogen technologies will expand to sectors where alternatives are less viable, including aviation and shipping, contributing to synthetic fuel production. These phases aim to create a robust hydrogen ecosystem, fostering regional and international supply chains and enabling renewable hydrogen to become a key energy carrier.

The European Parliament's Resolution on the European Hydrogen Strategy, adopted on May 19, 2021, reinforces the importance of hydrogen in achieving the EU's decarbonization goals. The resolution prioritizes sectors like industry, air and sea transport, and heavy haulage, where hydrogen's potential is most impactful. It calls for enhanced research, pilot projects, and industrial-scale demonstrations to make renewable hydrogen competitive and affordable. Recognizing hydrogen's strategic role, the resolution emphasizes international collaboration and the need for common standards to facilitate a global hydrogen market.

The EU Strategy for Integration of Energy Systems, introduced alongside the Hydrogen Strategy, advocates for a holistic approach to energy planning and management. It seeks to connect various energy sources and infrastructures to deliver efficient, low-carbon services across sectors. By promoting a circular energy system and increasing reliance on renewable hydrogen, the strategy aims to reduce waste, enhance energy efficiency, and decarbonize sectors like transport and industry that are otherwise challenging to address.

The Mission "Restore Our Oceans and Waters" complements these efforts by integrating hydrogen into sustainable maritime and aquatic solutions. Announced in 2023, this initiative aims to protect aquatic biodiversity, reduce pollution, and support the blue economy, with hydrogen-powered technologies playing a significant role in reducing emissions from waterborne transport and related activities.

The Sustainable and Smart Mobility Strategy, presented in December 2020, aligns closely with the Hydrogen Strategy by setting ambitious goals for reducing greenhouse gas emissions from transport by 90% by 2050. It emphasizes zero-emission solutions, including hydrogen-powered vehicles and ships, and supports infrastructure development such as refueling stations and retrofitted ports to facilitate the adoption of alternative fuels in maritime and inland waterway transport.

The Sustainable Blue Economy Strategy, adopted in May 2021, further underscores hydrogen's role in decarbonizing maritime transport and greening ports. By fostering innovation in renewable energy, including hydrogen, and promoting circular economy practices, the strategy aligns with the EU’s broader goals of environmental sustainability and economic resilience in coastal and maritime regions.

Finally, the REPowerEU Plan, introduced in 2022, accelerates the shift to renewable hydrogen as part of the EU’s strategy to reduce dependence on fossil fuel imports. It sets ambitious targets of producing 10 million tonnes of renewable hydrogen domestically and importing an additional 10 million tonnes by 2030. The plan prioritizes infrastructure development, including refueling stations and hydrogen pipelines, to integrate hydrogen into the EU’s energy system effectively. Through these measures, the EU aims to build a resilient and sustainable energy future while fostering international partnerships to advance hydrogen technologies globally.

The European Commission’s policies and strategies collectively establish a robust framework for integrating hydrogen into the EU's energy, transport, and industrial systems. Hydrogen is central to the EU’s ambition to achieve climate neutrality by 2050, as outlined in the European Green Deal. These strategies position hydrogen as a transformative energy carrier for decarbonizing hard-to-abate sectors, fostering energy security, and driving technological innovation.

The integration of hydrogen into maritime transport, supported by key policy initiatives, highlights its role in reducing greenhouse gas emissions and ensuring the sustainability of critical infrastructure. By leveraging regulatory frameworks and incentives, the EU fosters the deployment of renewable hydrogen, aligning with its broader climate goals. The focus on infrastructure development, tax incentives, and market mechanisms underpins the economic viability of hydrogen, ensuring its adoption across diverse sectors.

This comprehensive policy framework aligns closely with the objectives of the Joint Cross-Border Strategy, particularly in decarbonizing maritime transport and building a sustainable hydrogen ecosystem in the Adriatic-Ionian region. By consolidating efforts at national and regional levels, the EU’s hydrogen strategy ensures a harmonized approach to climate action, enabling the transition to a resilient and climate-neutral future while enhancing economic growth and regional cooperation.

5.2. Policies and Regulations – Croatia

Croatia's national energy and climate policies demonstrate a firm commitment to achieving decarbonization and transitioning to renewable energy sources, with hydrogen identified as a critical component in these efforts. The Integrated National Energy and Climate Plan (2021-2030) provides a comprehensive roadmap for reducing greenhouse gas emissions and increasing the share of renewable energy, aligning Croatia with the goals of the European Green Deal and the Paris Agreement. This plan emphasizes integrating hydrogen as a clean energy source, particularly in transport sectors such as maritime, where it holds significant potential to replace fossil fuels and reduce pollution in seas, rivers, and lakes. Furthermore, the plan supports the gradual conversion of aging fleets to alternative and hybrid solutions, co-financing projects that adopt hydrogen technologies and develop the necessary supporting infrastructure.

Building on this foundation, the Energy Development Strategy of the Republic of Croatia (2030 with a view to 2050) highlights long-term ambitions for integrating renewable energy into hydrogen production. Technologies such as Power-to-Liquids are pivotal in enabling the production of hydrogen and methane from renewable electricity, providing a clean and stable energy supply for maritime transport and other sectors. The strategy underscores the importance of leveraging Croatia's renewable energy potential while balancing environmental and spatial considerations, particularly in protected areas such as NATURA 2000. Similarly, the Low Carbon Development Strategy until 2050 complements these goals by projecting a gradual reduction in fossil fuel reliance and an increasing role for hydrogen in the national energy mix. This vision is underpinned by clear targets for renewable energy expansion and strategic investments in hydrogen infrastructure and technologies.

The Croatian Hydrogen Strategy (2050) specifically addresses hydrogen's transformative role in maritime transport. With a focus on decarbonizing ferry and port operations, the strategy emphasizes the importance of hydrogen as both an energy reservoir and a fuel for public and maritime transport, especially for connecting mainland regions with islands. Recognizing the unique geographical characteristics of Croatia, the strategy also considers hydrogen's role in supporting renewable energy integration and balancing supply and demand. The establishment of a Regional Hydrogen Centre is a cornerstone of this strategy, aiming to foster innovation, research, and development while enabling Croatia to actively participate in EU initiatives such as the Important Projects of Common European Interest (IPCEI). The Northern Adriatic Hydrogen Valley, involving partnerships with Italy and Slovenia, exemplifies Croatia's commitment to regional collaboration and its potential to contribute significantly to the European hydrogen ecosystem.

Croatia’s broader National Development Strategy until 2030 further reinforces these priorities by integrating hydrogen into efforts to enhance sustainable mobility and energy self-sufficiency. Investments in port infrastructure, research and development, and the promotion of alternative fuels all align with this vision. By adopting hydrogen technologies, Croatia not only positions itself as a regional leader in maritime decarbonization but also supports the EU’s overarching goals for climate neutrality by 2050. This alignment of national strategies with regional and EU priorities ensures that Croatia is well-prepared to contribute meaningfully to joint cross-border efforts, such as the development of a sustainable hydrogen-powered maritime network in the Adriatic region. The synergy between Croatia’s national policies and the objectives of the Joint Cross-Border Strategy provides a robust framework for addressing the challenges of decarbonization while fostering economic growth and technological innovation in the maritime sector.

5.3. Policies and Regulations - Italy

Italy's Hydrogen Strategy represents a cornerstone in the country’s decarbonization efforts and aligns closely with its Integrated National Energy and Climate Plan (PNIEC), as well as EU directives and the broader European Green Deal. The strategy envisions hydrogen as a transformative energy carrier capable of advancing Italy’s climate neutrality goals and addressing emissions in hard-to-abate sectors such as transportation, heavy industry, and energy storage. By focusing on renewable hydrogen production through electrolysis, the strategy aims to bolster energy security, reduce dependency on fossil fuels, and foster technological innovation.

A pivotal aspect of the strategy is the development of a national hydrogen ecosystem, with an emphasis on pilot projects and regional hydrogen valleys that integrate production, distribution, and consumption. These initiatives, such as hydrogen adoption in non-electrified railway lines in Sardinia and Sicily, demonstrate Italy's commitment to real-world applications of hydrogen technologies. In the transport sector, hydrogen is seen as a key solution for decarbonizing long-haul trucking and replacing diesel-powered trains, with infrastructure development focused on strategic routes and intermodal hubs.

The strategy also prioritizes industrial applications, targeting the transition from grey hydrogen to low-carbon alternatives in sectors like chemical manufacturing and oil refining. This transition not only reduces emissions but also sets the stage for scaling hydrogen solutions across Italy. The integration of hydrogen into the national gas grid through blending is highlighted as a near-term measure to stimulate market growth and familiarize industries with hydrogen technologies.

Under the National Recovery and Resilience Plan (NRRP), significant funding has been allocated to hydrogen development, including investments in green hydrogen production facilities, refueling stations, and hydrogen-compatible infrastructure. These investments aim to establish Italy as a leader in hydrogen innovation, creating new jobs and driving economic growth while achieving environmental sustainability. Collaboration with European partners and participation in initiatives such as the European Clean Hydrogen Alliance further strengthen Italy's position in the hydrogen sector.

By integrating hydrogen into its energy, transport, and industrial sectors, Italy's Hydrogen Strategy lays a solid foundation for achieving long-term decarbonization. The focus on pilot projects, infrastructure development, and regional collaboration ensures that the strategy aligns with EU goals while addressing national priorities. This approach positions Italy as a key player in advancing the Joint Cross-Border Strategy for Greening Maritime Routes, fostering a sustainable and interconnected hydrogen economy across the Adriatic region.

5.4. Other National Regulations

In this section, other relevant regulations from nations other than European are listed.

Individual sovereign governments have developed their own national regulations related to the production, transport, storage and application of hydrogen. An in-depth analysis of all global regulation is beyond the scope of this study. However, brief references and representative summary information is included in this subsection. Of particular interest to the application of hydrogen as a marine fuel are the considerations for flammability and gas dispersion.

United States

NFPA 2 Hydrogen Technologies Code. Edition 2

The National Fire Protection Association code was created to help establish fundamental safety measures for the production, installation, storage, piping, use and handling of hydrogen in compressed gas or cryogenic liquid forms.

This code is applicable to all occupancies and locations for the production, storage, transfer and use of hydrogen. Applications for permanent, mobile and vehicular infrastructure are included in the utilisation of hydrogen.

Other NFPA Codes that may apply to hydrogen systems or applications using hydrogen include (Blake, Buttner, & Rivkin, 2010):

- NFPA 52 Vehicular Fuel Systems Code
- NFPA 55 Standards for Storage, Use and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders and Tanks

NIST Handbook 130, The U.S. National Work Group (USNWG)

To address gaseous hydrogen refuelling applications, the U.S. National Institute of Standards and Technology (NIST) National Work Group (USNWG) for the Development of Commercial Hydrogen Measurement Standards continues to advocate for the adoption of new fuel-quality requirements and associated definitions for the NIST Handbook 130 (HB 130) Standard Specifications for Hydrogen Fuel.

U.S. 40 CFR Ch. I Subchapter J Part 370 Hazardous Chemical Release Reporting: Community Right-To-Know.

This part of the United States' Environmental Protection Agency (EPA) Code of Federal Regulations (CFRs) specifies information relating to the release of hazardous chemicals which require material safety data sheets or safety data sheets, with the intention of informing the public and communities surrounding any covered facilities about releases of hazardous chemicals.

U.S. 29 CFR Ch. XVII Part 1910 Subpart H: Occupational Safety and Health Standards: 103 Hydrogen.

While this is a standard regarding the safe operation for the protection of health, it covers basic design, construction, location, installation and operation of gaseous and liquefied hydrogen systems. Gaseous hydrogen system containers and safety-relief devices are to be designed, constructed and tested in accordance with the ASME Boiler and Pressure Vessel Code (BPVC), Section VIII. Liquefied hydrogen containers must also meet the requirements in the ASME BPVC; safety-relief devices are to meet the CGA Pamphlet S-1. For gaseous and liquefied systems, reference is made to the ANSI B31.1-1967 Industrial Gas and Air Piping Code for Pressure Piping for piping and tubing systems.

ASME B31.12-2019 Hydrogen Piping and Pipelines.

This American Society of Mechanical Engineers (ASME) Code covers the requirements for pipes used in gaseous and liquid hydrogen service and pipelines in gaseous hydrogen service. It covers materials, welding, heat treating, forming, testing, inspection, examination, operations and maintenance, in general.

ASME BPVC Section VIII Rules for Construction of Pressure Vessels. Division 1, Division 2-Alternative Rules and Division 3-Alternative Rules for Construction of High-Pressure Vessels.

This code in general addresses the design, fabrication, inspection, testing and certification of pressure vessels, including those that may be used for gaseous hydrogen service.

CGA S-1.1 Pressure Relief Device Standards – Part 1 – Cylinders for Compressed Gases & S-1.2 Pressure Relief Device Standards – Part 2 – Portable Containers for Compressed Gasses.

The U.S. Compressed Gas Association (CGA) publishes standards for handling gases, including pressure-relief devices for gaseous hydrogen or liquefied hydrogen containers.

CGA H-3: Standard for Cryogenic Hydrogen Storage.

This standard includes the minimum design and performance requirements for vacuum-insulated cryogenic tanks for liquid hydrogen limited by the maximum allowable working pressure.

CGA G-5.4 Standard for Hydrogen Piping Systems at User Locations.

This standard is intended to provide general information for designers, fabricators, installers, users and maintenance of hydrogen piping systems, as well as for safety personnel, fire departments, building inspectors and emergency personnel. It covers recommended principles for gaseous (Type I) or liquid (Type II) hydrogen.

CGA G-5.5 Hydrogen Vent Systems.

This standard directs the design, installation and maintenance of vents for hydrogen systems in gaseous and liquefied service. This publication supports other CGA Standards for hydrogen safety, utilisation and operations.

Australia

Standards Australia, ME-093 Hydrogen Technologies Strategic Work Plan.

A work plan for the business, technological, safety and environmental trends of the hydrogen industry has been developed by Standards Australia (AS). Based on ISO and IEC publications, the ME-093 Hydrogen Technologies committee determines the priority standards to be implemented. The plan's scope covers the use of hydrogen as an energy carrier along the entire value chain, including production, handling, storage, measurement, transport and distribution of either pure hydrogen or hydrogen mixed with other fuel gases. Applications for power and heat generation, home and industrial appliances, transportation, infrastructure for hydrogen refuelling and other end uses are included.

AS ISO 15916:2021 Basic considerations for the Safety of Hydrogen Systems.

AS has adopted international standards and made modifications, such as this document, modifying the ISO 15916 standard with additional Appendix ZZ listing variations for use of the standard in Australia.

AS 26142:2020 Hydrogen Detection Apparatus – Stationary Applications.

AS adopts the ISO 26142:2010 with modifications included in Appendix ZZ for use of the standard in Australia.

United Kingdom

The British Standards Institution (BSI) is recognised by the UK Government as the National Standards Body. It functions primarily to authorise and adopting international standards or European Directives into UK law, including the ISO, IEC, EC and other standards such as:

Pressure Equipment Regulations (PER) 1999.

These BSI Regulations implement the European Commission’s (EC) Pressure Equipment Directive (97/23/EC), which covers the design, manufacture and testing of pressure vessels and equipment.

Equipment and protective Systems for Use in Potentially Explosive Atmospheres (EPS) Regulations 1996.

These BSI regulations implement the requirement of the Atmosphères Explosibles (Explosive Atmospheres, or ATEX) Equipment Directive 94/9/EC regarding the design and manufacture of equipment for use in potentially explosive environments at places of work.

Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) 2002.

The BSI Regulations are similar to EPS but also cover the safety of workers and the workplace by offering minimum requirements for minimising the risks from explosive atmospheres, implemented in the requirement of the ATEX Workplace Directive 99/92/EC.

Japan

In Japan, there are no specific laws for using hydrogen. However, it is regulated as a high-pressure gas and is regarded as such within the scope of existing Japanese regulations.

Association of Hydrogen Supply and Utilization Technology (HySUT).

The goals of HySUT include ensuring stable supply and safe distribution of hydrogen. The association acts as a member to the ISO Technical Committee 197 (ISO/TC197) on Hydrogen Technologies. Several Guidelines for hydrogen technology are available from HySUT, including guidelines for quality control, metering, filling performance, testing setups and hydrogen-powered industrial truck filling. The focus of HySUT is primarily on the implementation of road-based hydrogen technologies, but it could expand to include hydrogen fuelled marine vessels.

High Pressure Gas Safety Act (Last version: Act No. 73 of 2005).

In general, this act is in place to regulate the production, storage, transportation, consumption and marketing of highpressure gases, including construction and the handling of high-pressure gas containers.

Regulation for Enforcement of the Air Pollution Control Act (Last version: Act No. 45 of 2017).

To protect the environment and monitor emissions, this act requires notification to local government of the emissions measurement from gas generators, including reformers for hydrogen production and fuel cells.

China

In China, hydrogen standards are managed by the Standardization Administration of the People's Republic of China (SAC).

Technical committees (TCs) focus on developing national standards for hydrogen, including:

- National Technical Committee of Hydrogen Energy (SAC/TC 309)
- National Technical Committee of Fuel Cell and Flow Battery (SAC/TC 342)
- Subcommittee of Electric Vehicles of National Technical Committee of Road Vehicles (SAC/TC 114/SC 27)
- Subcommittee of High-Pressure Vehicle Fuel Tanks of National Technical Committee of Gas Cylinders

(SAC/TC 31/SC 8)

- National Committees of Gases, Work Safety, Metallic and Non-Metallic Coatings (Yang, et al., 2019).

As of March 2022, SAC has approved the release of 101 national standards in the field of hydrogen energy, covering terminology, hydrogen safety, hydrogen production, hydrogen storage and transportation, hydrogen refueling stations, fuel cells and their applications.

GB/T 40045-2021 Fuel specification for hydrogen-powered vehicles -- Liquid hydrogen (LH2)

This document defines technical indications, test procedures and standards for fuel specification for hydrogenpowered vehicles - liquid hydrogen - packaging, marking, storage and transportation (for liquid hydrogen).

This standard applies to liquid hydrogen that is kept in storage tanks, pipelines, or tank trucks and utilised as the fuel for proton exchange membrane fuel cell vehicles.

GB/T40060-2021 Technical requirements for storage and transportation of liquid hydrogen

This standard specifies the requirements for the installation of liquid hydrogen storage vessel during the storage and transportation of liquid hydrogen, the transportation of tank cars and liquid hydrogen tank containers, purging and replacement, safety and protection and accident handling. This standard is applicable to technical requirements for the storage and transportation of liquid hydrogen vessels, liquid hydrogen transport vehicles and liquid hydrogen tank containers. This standard does not apply to the storage and transportation of liquid hydrogen in the military, national defence and aerospace fields.

GB/T40061-2021 Technical specification for liquid hydrogen production system

This document outlines the fundamental technical requirements for the liquid hydrogen production system, including the equipment needed for hydrogen liquefaction, liquid hydrogen storage, hydrogen discharge, automatic control and detection analysis, electrical facilities, lightning protection, anti-static and protective grounding and auxiliary facilities. It also addresses safety protection. This standard is applicable to the design of liquid hydrogen production systems that are newly constructed, rebuilt, or enlarged. Systems for producing liquid hydrogen, which are employed in the aerospace, national defence and military industries, are exempt from this standard.

Under these technical committees, ISO, IEC and national standards are adopted regarding hydrogen.

5.5. Alignment with EU and International Policies

Friuli-Venezia Giulia Region

In addition to the NAHV project, other projects are aligned to European Green Deal in the context of the NAHV initiative. In particular, Friuli Venezia Giulia (FVG) is implementing several regional policies described in the following paragraphs to support hydrogen development facilities.

Hydrogen Hub Trieste: This project, promoted by AcegasApsAmga (Hera Group), has received €14 million in funding from the PNRR. The hub involves the installation of a 2.5 MW electrolysis plant in the former Esso industrial area at the Port of Trieste. The plant will be powered by photovoltaic energy and water from the nearby waste-to-energy facility, producing up to 370 tons of hydrogen annually, primarily for land transportation.

Friuli Venezia Giulia Regional Research Infrastructure Projects: The region has approved the final ranking for funding research infrastructures in the renewable hydrogen sector. Key projects include:

- Fuse-Open Infrastructure on Future Underground Hydrogen Storage (UHS): This top-ranked project will establish an experimental infrastructure to identify and model potential underground hydrogen storage sites. It is led by OGS in collaboration with the universities of Trieste and Udine.

- I-CAMPUS-H2: This project aims to create a platform for the analytical characterization of strategic materials and processes for hydrogen. It will be developed in synergy with Sincrotrone Elettra, the laboratories of Area Science Park, and CNR.

- H2SmartLab: Presented by Area Science Park, this project envisions an advanced infrastructure for the production, storage, and use of green hydrogen, supported by an intelligent management system based on a digital twin.

- E4H2-Efficiency for Hydrogen: Led by the University of Trieste, with the University of Udine as a partner, this project will develop a distributed research infrastructure to improve energy efficiency in the green hydrogen value chain.

- Infrastructure for the Development of Advanced Materials and Processes to Support the Energy Transition in the Hydrogen Value Chain Coordinated by the University of Udine, this project will focus on developing advanced materials and processes to support the energy transition in the hydrogen value chain.

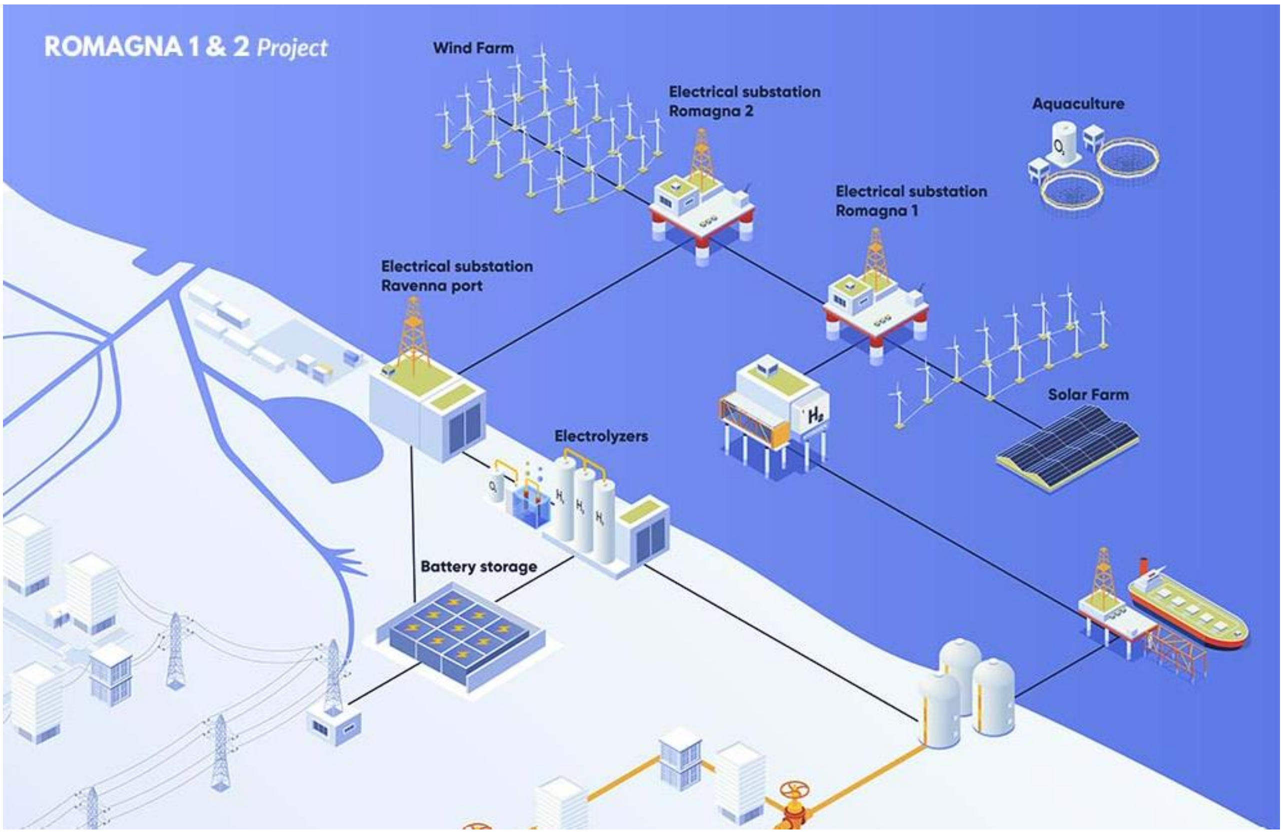
2025 Call for Proposals: The Friuli Venezia Giulia Region will launch a call for proposals in 2025 to support the production of renewable hydrogen. This funding includes €10 million from national funds and an additional €5 million from regional resources, aimed at promoting innovative and sustainable technologies for hydrogen production, in line with the European Green Deal goals. In October, an exploratory analysis was conducted, gathering 13 expressions of interest from the regional production system, amounting to a total value of €130 million.

Emilia Romagna Region

The Emilia-Romagna region actively aligns its maritime greening strategies with European and international policies, emphasizing the integration of hydrogen as a sustainable energy source. Key initiatives and projects underscore this commitment.

The regional policies of Emilia-Romagna are strongly focused on supporting hydrogen, in line with the objectives of the European Green Deal. The region has adopted strategic plans to promote decarbonization, encourage research, and attract investments in green technologies. Initiatives such as the "HYDROGEN VALLEY RAVENNA" project testify to the region's commitment to promoting a sustainable future, positioning itself as a virtuous example at the national and European levels. Collaborations between public entities, universities, and private companies further strengthen the port’s ability to attract investments and position itself as a reference model for the energy transition in the maritime sector. Dialogue with other European ports also contributes to the exchange of best practices and the development of common standards for hydrogen use, fostering a harmonized evolution of the sector.

The Agnes project represents a significant transformation of a traditional oil & gas district, such as that of Ravenna, into a renewable energy production hub. The idea is to install offshore wind turbines and floating solar plants, producing green hydrogen. Once completed, the project’s first phase will be able to provide energy to 500,000 households, covering all households in Romagna. Agnes involves a total investment of about 2 billion euros to install two wind farms in the Ravenna offshore area (Romagna 1 and Romagna 2), located over 12 miles from the coast, with a total capacity of 600 MW, plus 100 MW from a floating solar plant. A significant portion of the renewable energy produced will be fed directly into the grid, while a share will be used to power over 60 MW of electrolysis production, with plants located in an area of the port of Ravenna, capable of producing up to 8,000 tons of green hydrogen per year.



Primorje-Gorski Kotar County

Primorje-Gorski Kotar County is a key participant in the North Adriatic Hydrogen Valley project, a collaborative effort involving Croatia, Italy, and Slovenia. The initiative aims to establish a transnational hydrogen ecosystem, with the first hydrogen production targeted by the end of 2026. The project recently secured €25 million in grants, underscoring its strategic importance in regional decarbonization efforts.

The county's 2021-2027 Development Plan emphasizes energy efficiency and the integration of renewable energy sources. The Kvarner Regional Energy Agency (REA Kvarner) plays a pivotal role in supporting the development and implementation of energy efficiency and renewable energy projects, contributing to the county's energy transition.

These initiatives align with the European Green Deal's objective of achieving climate neutrality by 2050 and the Fit for 55 package's interim targets. The county's participation in cross-border hydrogen projects reflects its commitment to the EU Hydrogen Strategy and the development of alternative fuel infrastructure as outlined in the Alternative Fuels Infrastructure Regulation (AFIR).

Šibenik-Knin County

As of now, specific hydrogen projects in Šibenik-Knin County are not prominently featured in available sources. However, Croatia's national strategy includes 32 green hydrogen pilot projects at various stages of development, some of which may impact or involve this county.

Given the county's significant maritime activities and renewable energy potential, there are opportunities to develop hydrogen initiatives, particularly in decarbonizing maritime transport and integrating renewable energy sources. Aligning future projects with EU directives, such as the Renewable Energy Directive (RED II/III), could position Šibenik-Knin County as a contributor to national and European hydrogen goals.

Zadar County

Zadar County is involved in Croatia's broader push for green hydrogen, with several pilot projects underway. The county's strategic location and renewable energy resources make it a suitable candidate for hydrogen production and utilization projects.

Future plans may include the establishment of hydrogen refueling infrastructure to support maritime and land transport, contributing to the decarbonization of the region's transportation sector. These efforts would align with the EU's Alternative Fuels Infrastructure Regulation (AFIR) and the overarching goals of the European Green Deal.

Best practices from projects

Hydrogen as a fuel for heat engines has been a subject of discussion since the oil crisis in the 1970s. Since then, significant progress has been made in adapting hydrogen for use in gasoline engines, diesel engines, and gas turbines, demonstrating its practical viability. The primary benefit of using hydrogen lies in its emissions, which consist solely of water vapor, thereby eliminating the harmful CO2 output (Borkowski and John, 2021). In recent years, numerous projects have focused on integrating hydrogen technology into maritime transportation to reduce emissions and enhance sustainability. These initiatives, funded by various EU programs, aim to demonstrate the practicality of hydrogen as a marine fuel, develop the necessary infrastructure, and optimize energy management strategies. The following sections provide detailed insights into several key projects that have made significant contributions to the field, highlighting their objectives, achievements, and the impact they have had on advancing hydrogen usage in maritime transport.

Firstly, the MARANDA project, funded under the EU's Horizon 2020 program, focused on developing a fuel cell-based hybrid power system for marine applications. The goal was to demonstrate the feasibility of hydrogen fuel cells in marine environments and provide a zero-emission power solution for ships. After 5 years of project implementation, MARANDA project resulted in the development and validation of three automotive size fuel cell systems and a hydrogen storage solution. The project provided many valuable conclusions for the further development of fuel cell systems in maritime as well as other applications. In addition, many useful conclusions can be drawn from the specific issues that the team behind project MARANDA encountered during the implementation, such as issues with the time schedule of the project, the scope, lack of permission from the authorities, delivery of purchased components that are still in product development phase (such as hydrogen storage), and certain issues with safety systems (Ihonen et al, 2022).

The HySeas III project, funded by Horizon 2020, is noteworthy because it is the final part of a three part research program that began in 2013 looking into the theory of hydrogen powered vessels (HySeas I), followed by a detailed technical and commercial study to design a hydrogen fuel cell powered vessel (Hyseas II 2014-2015). HySeas III has determined beyond any doubt that the carbon emissions savings from the model vessel type will be very substantial – around an 80% reduction across the lifetime of such a vessel when compared to any equivalent conventional fossil-fuelled vessel. This view is also supported by Raucci (2017). It was also identified that the residual emissions associated with the vessel lay in the materials supply chain – the supply chain offering potential to further reduce overall emissions (Smith, 2022).

Another important contribution to the field was done by the H2SHIPS project, which aimed to facilitate the deployment of hydrogen-powered ships and the necessary refuelling infrastructure. It focused on developing technical and economic strategies to integrate hydrogen fuel into the maritime sector, including retrofitting vessels and establishing hydrogen bunkering facilities. The project developed an extensive platform which is openly accessible and regularly updated22. The platform contains news and events related to usage of hydrogen in maritime transportation, links to get involved in the network, projects database with a database of research projects and ships, and other resources such as education materials, legislative resources, and reports.

Some projects placed more emphasis on port infrastructure, such as the H2Ports project, funded by the FCH JU, which started in 2019 and focused on developing and testing hydrogen technologies to improve port sustainability. The importance of preparing port infrastructure was also identified by other, earlier Interreg IT-HR projects, such as METRO, which concluded that besides designing new ships, port infrastructure also needs to be properly prepared to fully support the new green ships, otherwise the overall results may be impaired. Project H2Ports activities included deploying hydrogen-powered equipment and refuelling infrastructure in ports, which are crucial for establishing hydrogen as a viable alternative fuel in maritime transport. The H2Ports project successfully introduced hydrogen technologies to port logistics, achieving the installation of Europe's first hydrogen refueling station in a port, and developing hydrogen-powered machinery, including a reach stacker and a yard tractor. These advancements aim to reduce greenhouse gas emissions, lower pollution, and improve operational efficiency in port areas.

The FLAGSHIPS project, another important Horizon 2020 initiative, is developing two commercially operated hydrogen fuel cell vessels, one which is a new design (Zulu 06), and a retrofit (FPS Waal). The project also strives to develop hydrogen bunkering infrastructure and establish a regulatory framework to support hydrogen use in inland waterway transport. The project aims to reduce the capital cost of marine fuel cell power systems significantly by leveraging knowhow from existing onshore and marine system integration activities. European supply chains for H2 fuel and FC system technologies are strengthened by networking through the project.

It is also important to note that maximum ecological benefits can only be achieved if the hydrogen powering these new and retrofitted ships is green, in other words, if the hydrogen is produced using renewable sources of energy. Example of a project that successfully developed solutions for this is the SeaFuel project, funded by the Interreg Atlantic Area program, which uses the expertise and infrastructure of the partners in renewable energy, namely solar, wind and marine, to demonstrate the viability of hydrogen as a fuel to be used by the local transport authorities. The project aims to create a sustainable hydrogen supply chain and develop refueling infrastructure for hydrogen-powered vessels. Another project which is a great example of how to potentially produce green hydrogen is the ITEG project - Integrating Tidal energy into the European Grid (from Interreg North-West Europe), which found that integrating tidal energy with hydrogen production is feasible and economically beneficial. The analysis showed that about 81-111 tonnes of hydrogen could be produced annually, with significant portions of tidal energy being exported to the grid due to the cyclical nature of tides. The optimization approach used in the study resulted in 41.5% higher annual profits and 47% higher carbon emission reductions compared to traditional methods. Furthermore, the project highlighted the advantages of dynamically operating electrolysers and the need for optimizing energy management strategies to improve system performance and cost-effectiveness (Alex, 2022).

One of the projects which is closely related to the FLAGSHIPS projects and serves as proof that successful solutions for the usage of hydrogen in maritime transportation is the ZEM Ports NS project. This project involved setting up a refuelling solution for the ships Maas and the aforementioned FPS Waal. It identified key lessons in legislation, infrastructure, standardization, and hydrogen production for vessel owners looking to decarbonize through hydrogen propulsion technologies. According to Chandrasekar and Godjevac (2023), legislation on hydrogen propelled vessel design, operations, the use of hydrogen as fuel, hydrogen production, and refuelling infrastructure are in very early stages of development. As a result, these regulations are often subject to change or are difficult to navigate as a clear policy framework has not been fully developed.

The authors, based on project results, conclude that vessel owners looking to retrofit hydrogen propulsion should keep in mind that regulatory hurdles and approvals do take a significant amount of time and require working in close cooperation with authorities, and class for approvals. Similarly, hydrogen infrastructure for production, distribution, and refuelling are all limited in availability. Although several major projects are planned or underway to improve the situation, it remains a significant challenge for operating hydrogen propelled vessels in the short-term. Current refuelling protocols dictate that the flow rate for gaseous hydrogen refuelling cannot exceed 60 grams/second. Taking a 1 ton storage system as reference, this flow rate would mean that refuelling would take roughly 4.6 – 5 hours, not including the time it takes to prepare (e.g. inspection, connection, disconnection) the storage system to be filled.

The use of swappable containers is a workaround to avoid long periods of refuelling using a shore-to-ship or ship-to-ship hydrogen refuelling system. However, enabling the effective use of a swappable container system requires a logistics network to transport to and from filling stations to the vessels, thereby increasing the cost of filling. One way to reduce the overall cost of a pool of containers is to have a large pool of widely usable containers that can be optimized to a large fleet of ships (e.g. four ships share six containers). The key challenge here would be to reach a certain level of standardization of the connections, safety, support systems, container size, and onboard integration of hydrogen containers within the fleet to allow for wide usage of the containers. In summary, legislation and infrastructure for hydrogen refuelling for a fleet of hydrogen propelled IWW vessels are limited and while temporary workarounds exist, optimally tackling these issues in the long term requires substantial investments in infrastructure and close collaboration between vessel owners, regulators, and hydrogen infrastructure providers (Chandrasekar and Godjevac, 2023).

Projects such as Condor H2 aim to resolve some of these challenges discussed by project ZEM Ports NS. Project Condor H2, initiated by the RH2INE network, brings together over 40 partners to enable emission-free inland and near-shore shipping on hydrogen using an innovative system of special 'tanktainers'. Condor H2 aims to develop a solution that involves fuel-cells with a battery pack and hydrogen storage on a pay-per-use basis, enabling zero-emission shipping with limited up-front investments for ship owners.

One of the most recent examples is the ZEAS PROJECT (Zero-Emission Adriatic Ship), led by Lürssen Design Center Kvarner from Rijeka. The project could be perceived as an amalgamation of all the previous work and knowledge in the field of hydrogen usage in maritime transportation, but the project promises to be much more. It involves 13 partners from Austria, Greece, Croatia, Norway, Germany, Slovenia, and Spain and it aims to develop a hydrogen-powered passenger ship to operate in the Adriatic Sea. Valued at EUR 18.9 million (EUR 13.5 million co-financed by the EU under Horizon Europe), it includes developing a zero-emission passenger ferry and associated hydrogen distribution, storage, and bunkering solutions. The ship's green powertrain includes hydrogen storage, fuel cells, electric motor, battery pack, safety system, and power management system. The project also involves emissions assessment, environmental performance studies, risk and safety assessments, and advanced digital technologies like digital twins and augmented reality for monitoring and predictive maintenance.

Funding Programs and Financial Support Mechanisms

The financial mechanisms supporting the development of hydrogen as a maritime fuel are crucial for advancing this technology and successful implementation. Two flagship EU research and innovation programs, Horizon 2020 and Horizon Europe, provide significant funding for projects that develop hydrogen technologies, including those for maritime applications. These programs are pivotal in driving innovation and supporting large-scale demonstrations of hydrogen technology integration.

Another vital funding source is the Connecting Europe Facility (CEF), which supports the development of sustainable and efficient transport infrastructure. CEF funding is instrumental in establishing hydrogen refuelling stations in ports, thus enabling the transition to hydrogen-powered maritime transport. Such funding programs are significant because they greatly reduce the financial burden on early adopters and help mitigate the risks associated with new technology adoption.

Additionally, various national and regional funding programs complement these EU initiatives, providing targeted financial support to projects that align with broader EU goals of sustainability and carbon neutrality. These funding mechanisms often cover a range of activities from research and development to the construction of infrastructure and pilot projects, ensuring a comprehensive approach to developing hydrogen as a viable maritime fuel. One very recent example of this comes from the Region of Friuli Venezia Giulia, and is titled "Non-repayable grants for the purpose of support for the establishment or modernisation of research infrastructures in the field of hydrogen from renewable sources". The aim of the grant is to increase and integrate the competitiveness of the entire regional system in the renewable hydrogen sector by sharing the research infrastructures created or modernised, with the aim of fostering interoperability, opening up to new markets, and acquiring new results of technological relevance and interest for the entire hydrogen value chain. Thanks to the widespread competences of the regional scientific system, it is intended to foster the creation of research infrastructures capable of activating collaborative research of interest to the scientific community and enterprises along the entire hydrogen value chain.

5.6. Conclusion

The use of hydrogen as a marine fuel represents a significant opportunity for decarbonizing the maritime sector, yet the lack of comprehensive regulatory frameworks at the national, regional, and international levels remains a critical barrier to its adoption. Although the International Maritime Organization (IMO) offers a risk-based "alternative design" approval process, and classification societies have introduced tentative guidelines for hydrogen-fueled ships, there is a pressing need for harmonized and comprehensive regulations. Marine and land-based regulations governing the generation, storage, transport, and use of hydrogen provide valuable references for its broader application in the maritime context. Drawing on lessons learned from the adoption of liquefied natural gas (LNG), the maritime industry can advocate for more robust regulatory developments, particularly within the framework of the European Commission's Fit-for-55 initiative, which underscores the EU's commitment to decarbonized and sustainable shipping.

To facilitate the adoption of hydrogen as a marine fuel, regulatory and policy measures must focus on several critical areas. At the international level, it is essential to support the IMO Sub-Committee on Carriage of Cargoes and Containers in developing interim guidelines for hydrogen as a marine fuel. Harmonization of the International Gas Carrier (IGC) Code with the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code) is also needed to include provisions for hydrogen combustion as cargo. Moreover, the IMO should request the development of marine fuel specifications and standardized couplings and procedures for hydrogen bunkering by the International Organization for Standardization (ISO).

At the national and regional levels, capacity-building initiatives should include the development of training and certification programs under the Standards of Training, Certification, and Watchkeeping (STCW) Convention and Code, ensuring seafarers are equipped to handle hydrogen technologies safely. Additionally, operators require guidance to meet obligations under the International Safety Management (ISM) Code for hydrogen-fueled ships. National policies must also address the environmental impacts of hydrogen production, particularly for large-scale renewable energy projects, to mitigate risks such as noise pollution, temperature changes, and biodiversity harm.

Amendments to the MARPOL Annex VI regulations are necessary to incorporate hydrogen-specific energy efficiency and NOx certification requirements. These amendments should introduce internal combustion engine limits for hydrogen and establish new emission regulations for hydrogen-fueled vessels, ensuring compliance with international environmental standards. Unified requirements for hydrogen-related machinery and equipment should be developed by the International Association of Classification Societies (IACS), alongside risk assessment guidelines for hydrogen bunkering and operations under the IGF Code.

To further support hydrogen's integration into the maritime sector, collaboration with organizations such as the Society for Gas as a Marine Fuel (SGMF) and the International Bunker Industry Association (IBIA) is crucial for producing industry best-practice publications and standards. Cross-border and international coordination is also vital to ensure alignment of regional and national regulations for renewable energy production. This will prevent market distortions, ensure equitable distribution, and avoid localized environmental impacts.

While hydrogen produced from renewable energy sources such as wind and solar can significantly reduce carbon emissions, it may also result in localized environmental impacts. These include changes to temperature equilibrium, noise pollution, and risks to marine biodiversity. Comprehensive national and regional policies must address these risks, and international standardization will be critical to ensure equitable and sustainable practices.

Implementing these recommendations requires a multi-stakeholder approach involving public entities, private industry, and research institutions. Such collaboration will accelerate technological advancements, reduce industry uncertainty through harmonized regulations, and ensure the safe and sustainable integration of hydrogen into the maritime sector. By addressing these regulatory and policy challenges, the maritime industry can position itself as a leader in the global energy transition, contributing to the European Green Deal’s objectives and advancing international climate goals.

6. Strategic Framework for Greening Maritime Routes

6.1. Developing a Clear Vision & Strategy

Croatia and Italy must establish a cohesive and actionable strategy for decarbonizing maritime transport. This strategy, aligned with TRANSH2 objectives, should prioritize hydrogen adoption while integrating broader EU goals, such as those outlined in the European Green Deal and Fit for 55 package. The strategy will act as a roadmap for investments, regulatory adjustments, and collaborative efforts necessary to achieve zero-emission maritime transport.

Vision

To create a sustainable, interconnected maritime transport network across the Adriatic, transforming the region into a leading hub for hydrogen-powered maritime mobility, contributing to a zero-emission future for the European maritime sector by 2050. This vision aligns with the European Green Deal's commitment to cutting emissions by 90%, fostering innovation, and ensuring environmental, economic, and social sustainability in cross-border maritime transport.

Mission

Our mission is to foster regional cooperation between Croatia and Italy to transition maritime transport towards hydrogen as a green fuel. Through collaborative efforts, we will develop the necessary infrastructure, innovate with cutting-edge technologies, and implement comprehensive policy frameworks to enable the widespread adoption of hydrogen in the maritime industry. By focusing on the decarbonization of cross-border maritime routes, we will contribute to EU environmental goals, enhance regional economic ties, and create a sustainable transport system for future generations.

6.2. Key Pilot Action Guidelines for Joint Cross-Border Strategy

Considering all gathered and described prerequisites, regional analyses, technological readiness levels, policy frameworks, and best practices, the following key pilot action guidelines are derived to facilitate the decarbonization of maritime transport and the adoption of hydrogen as a sustainable fuel:

- Adoption of Best Practices for Green Maritime Transport

Proven strategies for port decarbonization, green hydrogen integration, and energy efficiency improvements should be applied within the Programme Area, considering local needs, sustainability goals, and funding opportunities.

- Integration of Hydrogen and Renewable Energy Solutions

The deployment of hydrogen-powered vessels, shore power (cold ironing), renewable energy production (solar, wind, hydrogen electrolysis), and energy-efficient technologies (e.g., electrification of port operations, AI-based energy optimization) should be prioritized.

- Cross-Border Monitoring and Environmental Impact Assessment

The use of real-time environmental monitoring systems to track air and water quality, GHG emissions, and energy consumption in ports and along maritime routes should be established. Hydrogen refueling stations should be equipped with digital monitoring tools for transparent impact assessment.

- Institutionalization of a Cross-Border Hydrogen Maritime Cooperation Network

A permanent cooperation framework should be created to harmonize policies, facilitate knowledge exchange, and coordinate investments between Croatian and Italian ports, maritime authorities, and hydrogen industry stakeholders.

- Implementation of Pilot Projects for Hydrogen-Powered Maritime Transport

Key pilot actions should focus on retrofitting existing vessels for hydrogen fuel, developing hydrogen bunkering and refueling infrastructure, and testing zero-emission maritime mobility solutions on cross-border routes.

- Alignment with EU and National Hydrogen Strategies

The pilot actions should be designed to support the European Green Deal, Fit-for-55, and national decarbonization targets, ensuring compatibility with EU hydrogen policies, maritime regulations, and funding mechanisms.

- Development of a Pilot Implementation Plan

A structured plan should be established to deploy pilot projects in selected ports and routes, including port infrastructure adaptation for hydrogen refueling, Energy transition strategies for ports and vessels, Joint feasibility studies for large-scale hydrogen deployment, Policy recommendations for regulatory alignment.

- Cross-Border Impact Measurement and Evaluation

The environmental, economic, and operational performance of pilot projects should be systematically measured and compared using a unified methodology. Progress toward carbon neutrality goals should be evaluated to support further scalability.

- Policy Engagement and Financial Sustainability

National and regional policymakers should be involved in legislative alignment efforts to support hydrogen-based maritime transport. Funding mechanisms (EU programs, public-private partnerships) should be leveraged to ensure financial feasibility.

- Capacity Building and Stakeholder Engagement

Training and knowledge transfer should be provided to port authorities, maritime operators, shipbuilders, and local communities to facilitate the adoption of hydrogen technologies, infrastructure, and safety standards.

6.3. Cross-Border Collaboration Framework

The transition to hydrogen-powered maritime mobility across the Adriatic and its bordering regions requires a well-coordinated cross-border collaboration framework. This framework should harness the unique strengths of each region, promote synergy among stakeholders, and foster knowledge sharing and joint innovation. By aligning strategic goals and pooling resources, this collaborative approach aims to establish an efficient and sustainable hydrogen-powered maritime transport network that serves as a model for decarbonization.

6.3.1 Harmonized Policies and Regulations

One of the most significant challenges in cross-border collaboration is the harmonization of policies and regulations. Croatia and Italy must develop compatible regulatory frameworks that support hydrogen production, storage, distribution, and usage in maritime transport. Efforts should focus on promoting regulatory convergence, particularly in establishing safety standards for hydrogen handling and refueling infrastructure. By ensuring uniformity and compliance across borders, these regulations can create a stable environment for investment and innovation.

Achieving harmonization requires close cooperation between national and regional governments, as well as engagement with industry stakeholders and regulatory bodies. Collaboration should aim to align technical standards and certification processes, making it easier for businesses to operate across borders. For example, unified safety protocols for hydrogen storage and transport can prevent duplicative efforts and reduce operational risks. Regular dialogue between policymakers and maritime operators can also ensure that regulations are practical and responsive to the needs of the sector.

In addition to aligning existing regulations, it is essential to anticipate future developments in hydrogen technology and incorporate flexibility into the regulatory framework. This includes creating pathways for adopting emerging technologies, such as advanced hydrogen storage systems and refueling innovations. Policymakers should also consider the broader implications of regulatory harmonization, such as fostering cross-border trade and enabling joint investments in hydrogen infrastructure. By establishing a forward-looking approach, Croatia and Italy can ensure their regulatory frameworks remain robust and supportive of long-term maritime decarbonization goals.

6.3.2 Integrated Strategic Planning

Strategic planning is a cornerstone of successful cross-border collaboration. Aligning port development plans, energy transition strategies, and maritime transport policies across participating regions, including Primorje-Gorski Kotar, Šibenik-Knin, Zadar, Friuli Venezia Giulia, and Emilia-Romagna, is essential to ensuring a cohesive and unified transition to hydrogen-powered maritime mobility. Coordination should focus on identifying shared priorities and developing a roadmap that outlines key milestones, responsibilities, and timelines.

This alignment must extend to the implementation of hydrogen infrastructure. Identifying and prioritizing strategic ports for early adoption of hydrogen technologies is critical. Ports with high cross-border traffic, such as Rijeka, Trieste, and Ravenna, can act as hubs for initial deployment, creating a network that ensures the viability of hydrogen-powered routes. Joint action plans should include provisions for synchronized investments in refueling stations, hydrogen storage facilities, and supportive infrastructure.

Collaboration also involves planning for the integration of renewable energy sources into hydrogen production. By coordinating investments in solar and wind energy projects, regions can ensure a consistent and sustainable supply of green hydrogen. Strategic planning should also consider logistics and supply chain management, ensuring the seamless movement of hydrogen and related resources across borders.

6.3.3 Collaborative Investment

The transition to hydrogen-powered maritime mobility necessitates significant investment, which can be facilitated through collaborative approaches. National, regional, and EU funding mechanisms, such as Horizon Europe, Interreg, and the Recovery and Resilience Facility (RRF), provide critical resources for these efforts. Coordinating these funding streams across borders ensures that financial support is directed toward projects with the greatest impact.

Public-private partnerships (PPPs) play a pivotal role in mobilizing additional resources and fostering innovation. Governments and private stakeholders can collaborate to develop hydrogen production facilities, refueling stations, and hydrogen-powered vessels. Such partnerships not only attract private investment but also ensure that projects are designed and implemented efficiently, leveraging the expertise and capabilities of all involved parties.

By fostering a culture of collaboration and strategic investment, the Adriatic region can accelerate the deployment of hydrogen technologies, paving the way for a sustainable and interconnected maritime transport system. These efforts will not only advance regional decarbonization but also position the region as a leader in the global transition to zero-emission shipping.

6.4. Conclusion

The strategic goals of this Joint Cross-Border Strategy are designed to ensure that the transition to hydrogen-fueled maritime transport is achieved through collaboration, innovation, and sustained efforts across the regions. By harmonizing policies, developing integrated infrastructure, and fostering joint research, the strategy provides a comprehensive framework for decarbonizing maritime transport in the Adriatic region.

By leveraging existing regional strengths and aligning with EU goals such as the European Green Deal and the Fit-for-55 Package, the strategy prioritizes hydrogen adoption as a key element of the maritime sector’s energy transition. Collaborative efforts between Croatia and Italy, focusing on regions such as Primorje-Gorski Kotar, Šibenik-Knin, Zadar, Friuli Venezia Giulia, and Emilia-Romagna, will ensure the establishment of a sustainable and interconnected hydrogen-powered transport network.

The strategy emphasizes building the necessary hydrogen infrastructure, including refueling stations, production facilities, and integrated supply chains, while fostering innovation through joint research projects and pilot initiatives. By aligning regulatory frameworks and engaging stakeholders at all levels, the strategy ensures the development of a robust environment for investment and technological advancement.

This collaborative framework not only addresses the technical and logistical challenges of transitioning to hydrogen but also focuses on broader socioeconomic benefits, such as job creation, environmental improvements, and community engagement. By pooling resources and expertise, the strategy aims to position the Adriatic region as a leader in hydrogen technologies, setting a benchmark for maritime decarbonization efforts globally.

Ultimately, the strategy's success will be measured by its ability to reduce emissions, enhance cross-border connectivity, and contribute to EU targets for zero pollution in European waters by 2050. Through coordinated action and shared commitment, this Joint Cross-Border Strategy serves as a model for sustainable maritime transport, ensuring a cleaner and more resilient future for the region.

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