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D3.1.1 - Joint report (handbook) of an intelligent solution for planning and replication of green transition

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Contents

1. Project Overview	5
2. Document Overview	6
3. Hydrogen as Green Fuel for Maritime Transport	6
3.1 Production of Hydrogen	6
Hydrogen Technology Readiness	6
Properties of Hydrogen	7
Hydrogen production technologies	8
Level of Maturity of Technologies.....	13
Developments in the Production Capacity of Green Hydrogen	15
3.2 Hydrogen Storage Technologies	32
Hydrogen Integration on Board Ships	34
Hydrogen Bunkering.....	37
3.3 Sustainability	38
GHG Performance	38
Air Pollution.....	44
Other Environmental Impacts.....	46
3.4 Use of Hydrogen	49
3.5 Conclusion on hydrogen's usability as fuel in maritime transport.....	50
4. Regulatory and Policy Considerations	54
4.1 Regulations for EU Member States	54
4.2 Policies and Regulations – Croatia	58
4.3 Policies and Regulations - Italy	59
4.4 Other National Regulations.....	60
4.5 Alignment with EU and International Policies.....	65
4.6 Conclusions on hydrogen use feasibility	73
5. Selection of optimal configuration for hydrogen fuelled passenger vessels	76
Hydrogen Storage	76
Fuel Distribution System.....	80

Energy conversion	80
Other aspects of the hydrogen system	84
6. Multicriteria Analysis	87
Methodology of multi-criteria assessment	90
Results of the multicriteria assessment	94
7. General recommendations for the hydrogen implementation on board	96
Hydrogen Storage and Containment Safety	96
Fire and Explosion Risk Mitigation	96
Crew Training and Emergency Response	97
Regulatory Challenges and Future Outlook	97
Vessel design	98
8. Conclusions on the optimal configuration selection	101
9. Route selection for hydrogen powered passenger vessels	103
Environmental evaluation	103
Air quality	103
Natura 2000 sites	106
Navigational analysis	107
Transport models	110
Environmental analysis	114
Air quality	114
Natura 2000 sites	119
Navigational analysis	121
Characteristics of the Tronchetto-Lido maritime route	121
Meteorological and oceanographic conditions	123
Transportation analysis	126
Air quality	131
Natura 2000 sites	137
Navigational analysis	138
Characteristics of the Split-Supetar maritime route	138

Italy – Croatia



Transportation analysis	141
Environmental analysis.....	145
Air quality	145
Natura 2000 sites	149
Navigational analysis.....	150
Characteristics of the Ancona-Split maritime route	151
10. Business Model of Cooperation	160
11. Financial Construction	162
12. Investment and economic feasibility	164
12.1 Overview on funding and investment mix in Italy	164
12.1.1 EU funding & grants (non-dilutive support)	164
12.1.2 National funding (Italy)	165
3. Regional funding (Friuli Venezia Giulia).....	166
12.1.3 Green / Blue Bonds & Thematic Capital Markets Instruments	168
12.1.4 Commercial Debt & Institutional Investors	169
12.2 Overview on funding and investment mix in Croatia	171
12.2.1 National Support for Hydrogen Refuelling Stations (HRS)	171
12.2.1.2 EU Funds & CEF/AFIF (Alternative Fuels Infrastructure Facility).....	172
12.2.3 Local / Regional Context — Zadar & EU Funds Awareness	176
12.3 Summary of key findings	177
13. Applicability to Other Adriatic Ports	179
Interpretation of the Matrix	182
Practical Use of the Matrix	183
Contribution to Cross-Border Scalability	183

1. Project Overview

The analysis of the program area highlights a significant number of ports along the Adriatic coast and underscores the urgent need to enhance the sustainability of port infrastructures. This will be achieved by adopting low-carbon transportation and mobility solutions, particularly through the modernization and sustainability of cross-border (CB) maritime connections. The primary goal of the project is to improve sustainable cross-border sea mobility by showcasing viable applications of zero-emission fuels, such as green hydrogen, in maritime transport routes. This involves the introduction of these innovations to port authorities, transport operators, and stakeholders across the region.

The initiative aims to transition cross-border maritime transport towards sustainability by demonstrating innovative solutions and drafting detailed investment plans. This commitment will support the increase in the use of zero-emission fuels by 2050, aligning with the European Green Deal's objective to cut maritime sector emissions by 90%. It directly contributes to the EU's mission to "Restore our Ocean and Waters" by aiming for zero pollution and reduced greenhouse gas emissions in EU waters.

To support the Italian and Croatian economies through a complete hydrogen supply chain in maritime transport, the project emphasizes the need for further research and innovation. It focuses on developing hydrogen-powered vessels and the necessary refueling infrastructure in ports, aiming to meet the European Sustainable and Smart Mobility Strategy's 2030 target for market-ready zero-emission vessels.

Key activities include researching and analyzing options for greening maritime transport links, developing hydrogen-powered solutions for cross-border and local passenger transport, and designing innovative concepts for hydrogen-fueled passenger ships. The project will also conduct feasibility studies for pilot areas on introducing hydrogen refueling stations in ports.

The adoption of new technologies presents a unique opportunity for the region to address environmental challenges and enhance the safety, cleanliness, and efficiency of transport. This endeavor requires cross-border cooperation and the exchange of knowledge in developing and promoting sustainable sea mobility solutions.

However, deploying hydrogen in maritime transport faces significant challenges that demand collective efforts from both the private and public sectors. Overcoming these obstacles requires substantial investment, supportive regulatory and safety frameworks, ongoing research, innovation, and the establishment of a refueling infrastructure network in ports.

2. Document Overview

Joint report describes in details new solution for planning and replication in Adriatic Sea and beyond, including methodologies and tools for usage in process of planning and application. Handbook will present also final business model of cooperation and financial construction.

3. Hydrogen as Green Fuel for Maritime Transport¹

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

3.1 Production of Hydrogen

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.

¹ 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.

Italy – Croatia



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Properties of Hydrogen

At atmospheric temperature and pressure, hydrogen is a colourless gas without a smell. Its main properties are displayed in Table 1.

Table 1 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 (°C)	585	250
Liquid density (kg/m ³)	70.8 (at -253 °C)	840 (at 15 °C)
Adiabatic flame temperature at 1 bar (°C)	2127	2000
Molecular weight (g/mol)	1.007825	54
Melting point (°C)	- 259	-26
Boiling point (°C)	-253	154
Flash point (°C)	N/A	60
Critical temperature (°C)	-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

Hydrogen production technologies

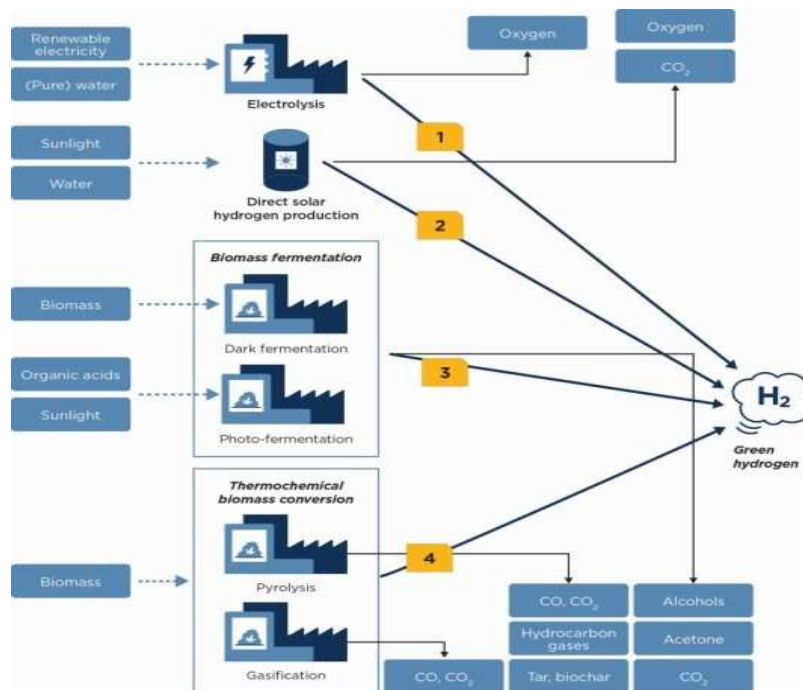
Hydrogen is increasingly recognized as a clean fuel with significant potential for decarbonizing the maritime sector, particularly as it can be produced from renewable energy sources through electrolysis. However, its adoption in maritime applications is influenced by storage methods, each with distinct 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 1. Production pathways for green hydrogen



Pathway 1 - Electrolysis

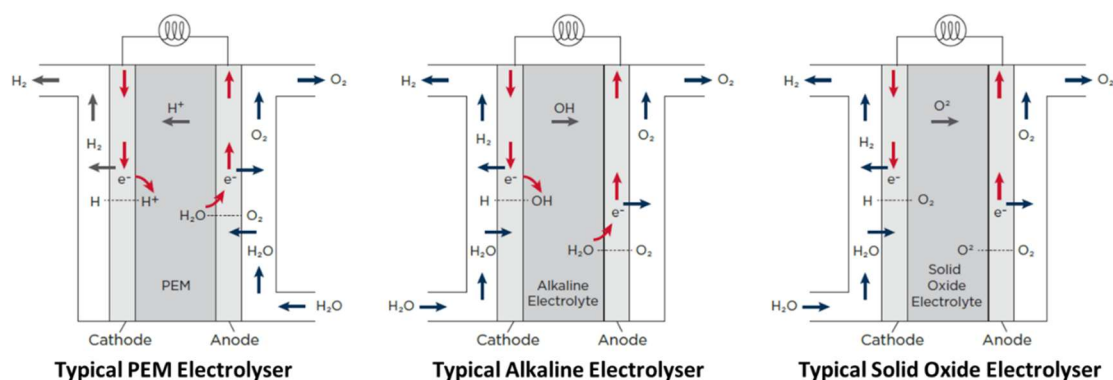
Electrolysis is the most scalable method for producing green hydrogen, using renewable electricity to split water into hydrogen and oxygen. Recognized under the EU's Renewable Energy Directive (RED) as a renewable fuel of non-biological origin (RFNBO), this process is central to the decarbonization of 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 2 Electrolyser technologies currently available or under development



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 2 Summary comparing different types of electrolyzers

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/m ²]	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 CO₂, offering a low-energy alternative to thermochemical processes. It comprises:

- Dark Fermentation, an anaerobic process, decomposes biomass into hydrogen and CO₂, 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 CO₂ 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.

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) electrolyzers. Alkaline electrolyzers have been fully proven in operational environments, while PEM electrolyzers 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 3, 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 31 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	9	(Rouwenhorst, Van der Ham, Mul, & Kersten, 2019), (Smith, Hill, & Torrente-Murciano, 2020)
	PEM electrolyser		8-9	(Smith, Hill, & Torrente-Murciano, 2020)
	SOEC			(Rouwenhorst, Van der Ham, Mul, & Kersten, 2019),

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	electrolyser	electricity	3-5	(Smith, Hill, &
Production pathway	Technologies	Remarks	Technology readiness level (TRL)	Sources
				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 Hincio, 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 Hincio,
	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.

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

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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 4, 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.

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Table 4 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	

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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)	Murchison Hydrogen Renewables Pty Ltd. (Parent company: Copenhagen Infrastructure					

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(HyResource, 2022)	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					Up to 5,000 tonnes per day in ammonia will be produced from

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		Australia	3 GW	Unknown	Announced	2023	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	Start of operation (year)	Remarks

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Base One (Collins L. , 2020)	Energix 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.

Italy – Croatia



Sinopec Xinjiang Kuqa green hydrogen pilot project (Balkan Green Energy News, 2022) (NS Energy Business, 2021)	Sinopec, Petroleum	China	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	China	< 5 GW	400-500	Under construction	Before 2025 Use of onshore wind and solar.
Unnamed (Greater Copenhagen) (S&P Global, 2021) (World-Energy,	Orsted, A P MollerMaersk, DSV Panalpina, DFDS, SAS and Copenhagen					Announced (feasibility study	First phase 2023: 10MW electrolyzer. By 2027: 250 MW. By

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2020)	Airports	Denmark	1.3 GW	250	underway)	2023	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 Esbjerg. 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 Esbjerg. The hydrogen will be used as a truck fuel.

Italy – Croatia



Fortescue project (PV Magazine, 2022) (Scully, 2022)	Fortescue Industries, Egyptian Government	Future 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.

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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	

Italy – Croatia



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)	SVEVIND group, ILF Consulting Engineers, Kazakh						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.

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(Rec-kaz, 2021)	Government	Kazakhstan	30 GW	3,000	Announced	2028	
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

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						regions.
Beijing Jingneng Inner Mongolia (Statista, 2021) (Brown & Grünberg, 2022) (World-Energy, 2020)	Beijing Jingneng Clean Energy Co.	Mongolia	5 GW	400	Under construction	Unknown (2021 was planned)
NorthH2 (FuelCellsWorks, 2022) (NorthH2, 2022)	Groningen Seaports, Eneco, RWE, Equinor, Shell, Gasunie, OCI, Province of Groningen	Netherlands	>10 GW	1,000	Announced (Feasibility studies underway)	2027 Planning to generate at full capacity in 2040.

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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	
GreenH2Atlantic (Green H2 Atlantic, 2022)	Axelera, Bondalti, CEA, DLR< EDP, Efacec, ENGIE, Galp, ISQ, Inesctec, Martifer Group, McPhy and						Located at the port of Sines. Start of construction planned in 2023 and completion expected in

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(ENGIE, 2021)	Vestas	Portugal	0.1 GW	10	Announced	2025	2025.
MadoquaPower	CIP, Madoqua						
2X (Klevstrand, 2022)	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

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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

3.2 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 ($\sim 40 \text{ kg/m}^3$ 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/m^3), 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 3 Summary of different hydrogen storage technologies

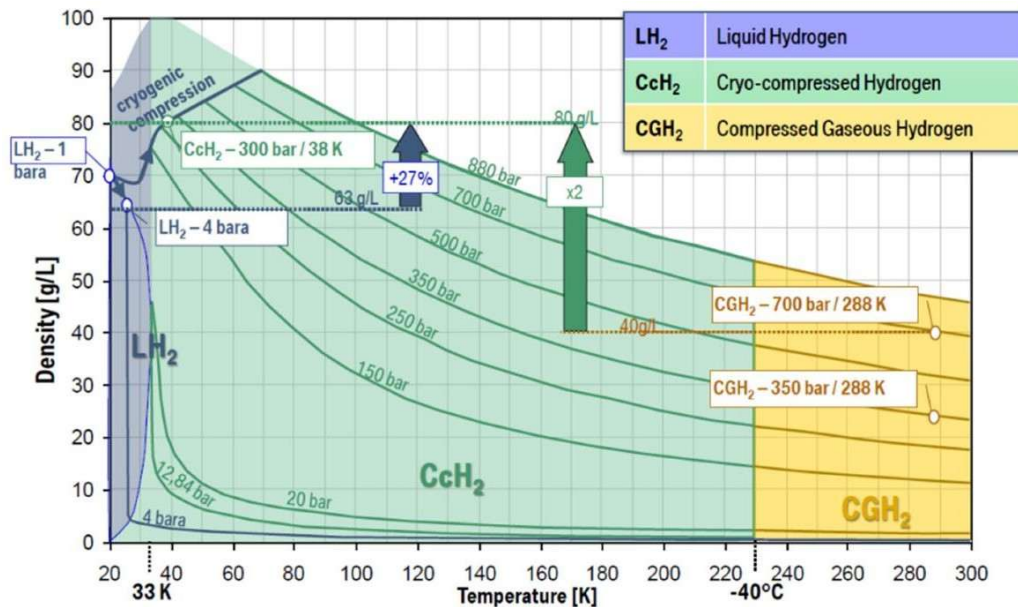
Hydrogen Storage Technology		Advantages	Disadvantages	Current State	TRL
Physical Storage Methods	Compressed hydrogen	-Relatively mature -Many types of storage tanks for different areas -Purity	-Storage density needs to be improved -Cost needs to be reduced	-Successfully used for trains -Mass production	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 4 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 (LH₂) 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 4 Hydrogen density versus pressure and temperature



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:

- SUISEI FRONTIER – A hydrogen carrier with a cargo capacity of 1,250 m³ in vacuum-insulated LH₂ 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 LH₂ 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.

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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, LH₂ 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.

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	Primarily a test platform for hydrogen tech.
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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.
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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 SUIISO 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.
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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.
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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.

Hydrogen Bunkering

Hydrogen bunkering is probably one of the less mature aspects of hydrogen technology. Referring to CH₂, several filling and refuelling stations already exist throughout the world. When it comes to LH₂, 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 LH₂ 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 5 LH2 bunkering facility for ships, custom-designed for the MF HYDRA



3.3 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.

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 CO₂ 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 (LH₂) 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 CO₂ eq/MJ hydrogen
 - Solar-powered liquefaction: 11.7g CO₂ eq/MJ hydrogen
 - Grid-powered liquefaction: 43.3g CO₂ 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, CO₂ 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 CO₂, CH₄, and N₂O, converted to CO₂-equivalents (CO₂-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.

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- 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 5 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)	Upstream emissions depend on crude oil
			FuelEU Mari	

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MGO	-	91	time proposal	source and refinery
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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 CO₂ or methane (CH₄), 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 (LH₂), 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.

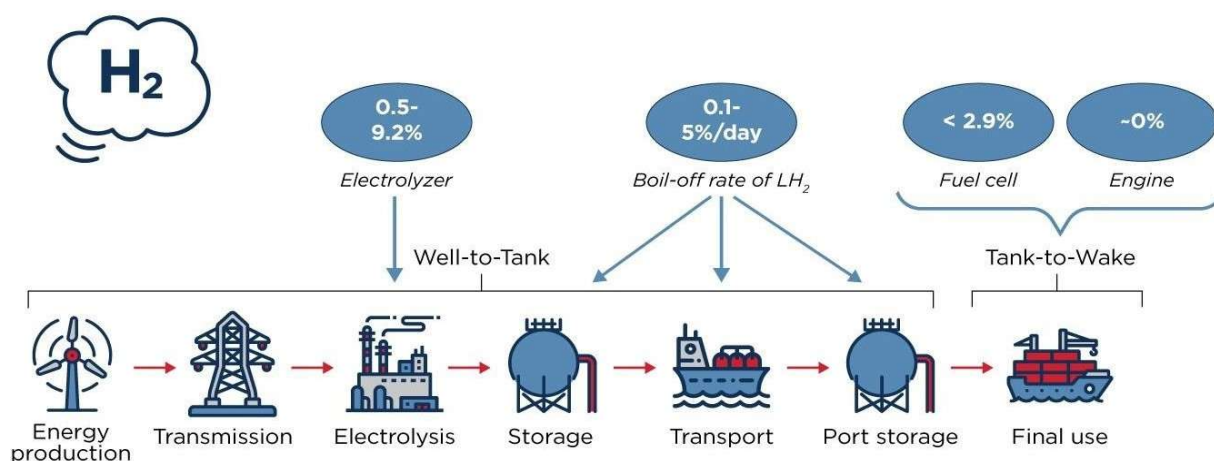
- Electrolysis: Hydrogen venting and purging during production can lead to losses of up to 9.2% if not properly recovered. However, best-practice systems can minimize this to below 0.52%.
- Fuel Cells: Small amounts of hydrogen are lost through venting and purging, accounting for approximately 2.9% of 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 6. 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 CO₂ and CH₄ 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 (CO₂), 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 (CO₂) = 1 (baseline for all GWP calculations).
- Fossil methane (CH₄) = 29.8 ± 11 .
- Non-fossil methane (CH₄) = 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 7. GHG impact of hydrogen emissions

Aspect	Value	Source	Remarks
Global warming potential of hydrogen over a period of 100 years (GWP₁₀₀)	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	0.4% (assuming a H ₂ leaking rate of 1%)	Warwick et al (2022)	In a scenario in which 40% of final fossil

offset by hydrogen leakage.	4% (assuming a H ₂ leaking rate of 10%)	energy consumption is replaced by hydrogen.
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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.

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 (SO₂), 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).

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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.

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.

Italy – Croatia



TransH2

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 CO₂ 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.



3.4 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, Zadar, Trieste and Monfalcone, 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 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.

3.5 Conclusion on hydrogen's usability as fuel in maritime transport

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 8. 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
	Photo-electrolysis	10% **	1-3
	Thermolysis	20-45% **	3-4

Italy – Croatia



TransH2

2. Direct solar hydrogen production	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 CO₂, SO₂, 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 9. 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				
N₂O	Present	Present	Not present	Not present
CH₄	Low	Present at Otto engines	Not present	Not present
CO₂	Present	Present	From manufacturing wind turbines and solar panels	From manufacturing wind turbines and solar panels

H₂ (indirect)	Not present	Not present	From venting, purging and boil-off	From venting, purging and boil-off
Air pollutant emissions				
SO₂ 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 (LH₂) 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,

Italy – Croatia



TransH2

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.

4. Regulatory and Policy Considerations

4.1 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

Italy – Croatia



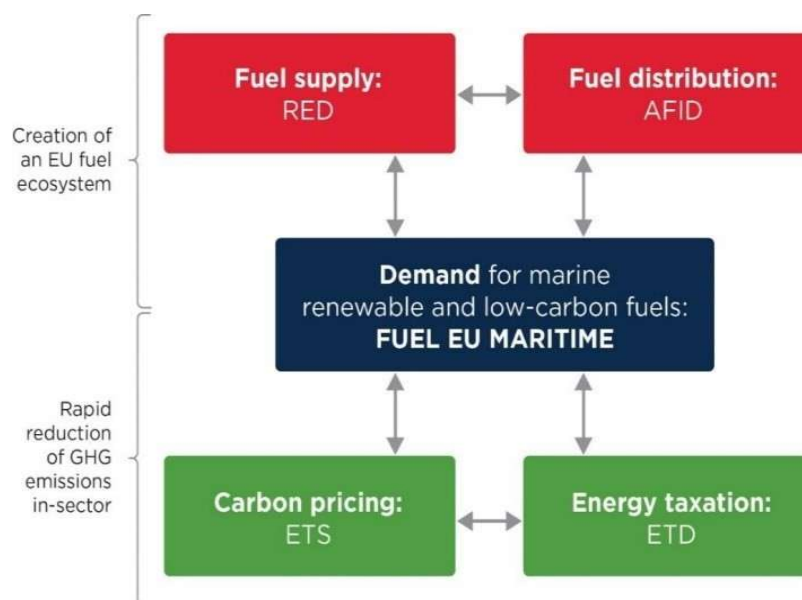
TransH2

the development of hydrogen-compatible infrastructure and calls for increased investments in research, pilot projects, and the commercialization of hydrogen technologies.

Figure 7. The European Commission 'Fit-for-55' package



Figure 8. 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 electrolyzers 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.

Italy – Croatia



TransH2

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

Italy – Croatia



TransH2

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.

4.2 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

Italy – Croatia



TransH2

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.

4.3 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. In line with this national framework, regional authorities are also advancing hydrogen initiatives; for example, the Friuli Venezia Giulia Region approved its Regional Hydrogen Strategy (Strategia Regionale Idrogeno) in December 2025, reflecting the increasing involvement of regional authorities in hydrogen policy implementation in Italy.

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

Italy – Croatia



TransH2

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.

4.4 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):

Italy – Croatia



TransH2

- 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.

Italy – Croatia



TransH2

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 Gases.

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.

Italy – Croatia



TransH2

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.

Italy – Croatia



TransH2

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).

Italy – Croatia



TransH2

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.

4.5 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. Overall, public resources mobilised in Friuli Venezia Giulia for hydrogen-related initiatives amount to approximately €333.5 million, including €21 million from the PNRR, €240.5 million linked to PNRR-IPCEI initiatives, €12 million from EU programmes under direct management, €50 million from regional resources, and €10 million from national funds (MASE flagship projects).

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. Within the PNRR Mission 2 – Component 2 – Investment

Italy – Croatia



TransH2

3.1, a total of €15.8 million has been allocated for renewable hydrogen production plants in brownfield industrial areas in the region. The Hydrogen Hub Trieste project, implemented by AcegasApsAmga S.p.A. (lead partner) together with HestAmbiente S.r.l., is currently authorised and under construction and will produce approximately 400 tonnes of hydrogen per year.

Friuli Venezia Giulia Regional Research Infrastructure Projects: The region has approved the final ranking for funding research infrastructures in the renewable hydrogen sector. This initiative is funded under Regional Law LR 13/2023 (Art. 7) with a total allocation of €11.2 million. 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.

Additional Research and Innovation Initiatives

Complementary initiatives funded through regional and national resources support hydrogen research activities across the regional innovation ecosystem. Under the PSC programme and LR 13/2023, a total of €4.7 million has been allocated to research organisations including Area Science Park, CNR-IOM, Elettra Sincrotrone Trieste, OGS, SISSA, the University of Trieste and the University of Udine. These initiatives are expected to generate approximately 37 new research contracts and support projects such as SURFACE, i-CAMPUS-Op, IHOST, RISE-H2 and the Udine Hydrogen Research Center (UD-H2).

Italy – Croatia



TransH2

Hydrogen in Public Transport

The region is also promoting hydrogen deployment in public transport through pilot projects in the cities of Trieste and Monfalcone under the PREPM-TPL programme (Regional Resolution DGR 588/2023).

In Trieste, feasibility studies are ongoing for hydrogen supply and the design of a refuelling station, with the objective of deploying 10 hydrogen buses between 2028 and 2030 as part of the progressive electrification of the urban fleet.

In Monfalcone, the programme foresees the introduction of 15 hydrogen buses, with eight vehicles expected by 2026. In parallel, a hydrogen production and refuelling plant is under development (1 MW electrolyser, 400 kg/day hydrogen production capacity, powered by renewable electricity including 1.67 MW of photovoltaic energy). These initiatives aim to support the decarbonisation of local public transport and the development of a regional hydrogen value chain.

Additional investments under the PNRR programme (Mission 2 – Component 2) include hydrogen refuelling infrastructure projects developed by Q8 Petroleum Italia in Porpetto (€1.7 million) and APT Gorizia in Monfalcone (€3.5 million).

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.

Two projects have been selected within this framework: the SOLHX project promoted by Cantiere Navale di Venezia (grant €8.4 million) and the ABS Renewable Hydrogen Production project promoted by Bertoli Safau S.p.A. (grant €6.5 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

Italy – Croatia

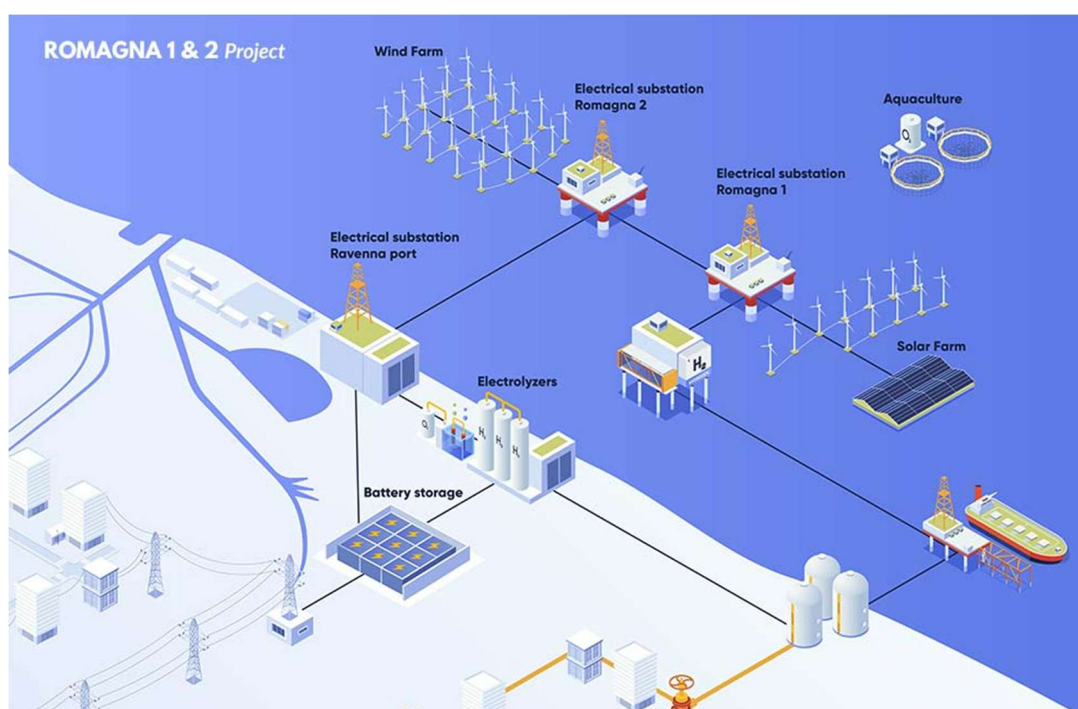


TransH2

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. The layout of the proposed project is shown in Figure 9.

Figure 9. Romagna 1 & 2 Project



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.

Italy – Croatia



TransH2

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

Italy – Croatia



TransH2

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

Italy – Croatia



TransH2

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 electrolyzers 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

Italy – Croatia



TransH2

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

Italy – Croatia



TransH2

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.

4.6 Conclusions on hydrogen use feasibility

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

Italy – Croatia



TransH2

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.

Italy – Croatia



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.

5. Selection of optimal configuration for hydrogen fuelled passenger vessels

The design of an efficient and safe energy system layout is a fundamental aspect of integrating hydrogen propulsion on board. The energy system consists of several interrelated components, including hydrogen storage, fuel distribution, power conversion, and thermal management. The optimal configuration of these elements directly impacts vessel efficiency, operational range, safety, and compliance with maritime regulations. Given the challenges associated with hydrogen as a marine fuel, including its low volumetric energy density, flammability, and cryogenic storage requirements, careful planning of the energy system layout is necessary to ensure seamless operations and reliability.

Hydrogen Storage

The selection of an appropriate hydrogen storage method is one of the most critical factors in the energy system design. Storage technologies must balance energy density, safety, system weight, integration complexity, and regulatory compliance. Broadly, hydrogen storage methods can be categorized into physical-based and material-based technologies. Each has specific characteristics that influence its suitability for maritime use.

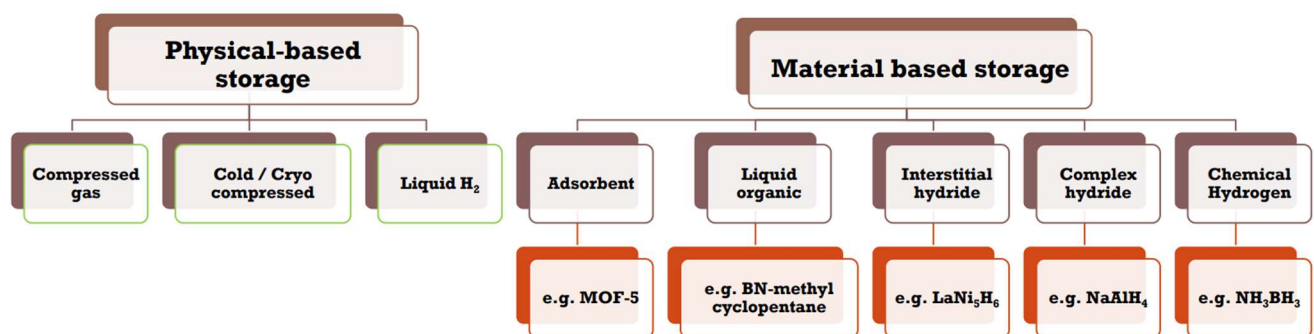


Figure 5-1 Hydrogen storage options

Compressed hydrogen storage involves storing hydrogen gas in high-pressure vessels, typically at 350 bar (used for larger vessels or buses) or 700 bar (used in automotive and limited vessel applications). These tanks are made of advanced composite materials (Type III or IV) to withstand the high internal pressures while minimizing weight.

- Advantages:

- Commercially mature and widely available
- Fast refuelling capability
- Relatively simple integration into existing ship architectures
- Challenges:
 - Low volumetric energy density ($\approx 23 \text{ kg/m}^3$ at 350 bar)
 - Requires large tank volume for long-range operations
 - Safety considerations related to high-pressure containment



Figure 10-1 Compressed hydrogen tanks

Compressed hydrogen is particularly suited for short to medium-range passenger vessels and ferries where frequent refuelling is feasible. Compressed hydrogen (CH_2) at 350-700 bar is the most widely used storage method due to its maturity and relatively straightforward implementation. However, high-pressure storage requires reinforced tanks, which increase vessel weight and occupy significant onboard space (Zhou et al., 2021).

Liquid hydrogen is stored cryogenically at -253°C in vacuum-insulated double-wall tanks. This method offers higher volumetric energy density compared to compressed hydrogen, making it attractive for longer-range or high-power vessels.

- Advantages:
 - High volumetric density ($\sim 70.8 \text{ kg/m}^3$)
 - Lower storage pressure (1–10 bar)
 - Suitable for large vessels with high hydrogen demand (e.g. cruise ships, RoPax)
- Challenges:
 - Significant energy input for liquefaction ($\sim 30\%$ of H_2 energy content)

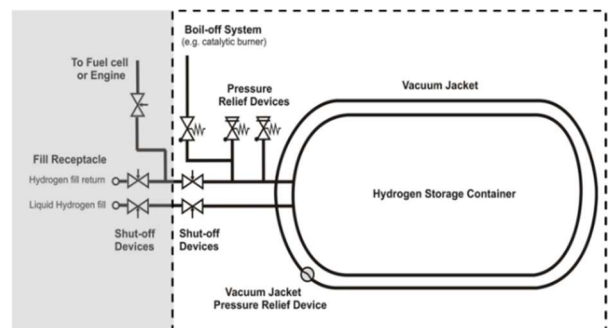


Figure 10-2 Liquid hydrogen storage

Italy – Croatia



TransH2

- Boil-off losses during storage and operation, requiring either reliquefaction or controlled venting of excess hydrogen.
- Complex cryogenic tank systems and safety management
- Limited commercial availability in the marine sector



Figure 10-3 Liquid hydrogen tanks based on swappable concept developed in sHYpS EU co-funded project

While LH2 presents challenges in terms of infrastructure development, it is increasingly being adopted in maritime projects, as demonstrated by the MF Hydra ferry in Norway, the world's first operational liquid hydrogen-powered vessel and as studied in the on going EU project sHYpS.

LOHCs are liquid compounds (e.g. dibenzyltoluene) that chemically bind hydrogen and release it via a catalytic dehydrogenation process at high temperatures (250–320 °C). The liquid form allows use of conventional fuel infrastructure and tanks.

- Advantages:
 - Ambient temperature and pressure storage
 - High safety (non-toxic, non-flammable in hydrogenated state)
 - Compatible with existing liquid fuel logistics
- Challenges:
 - High thermal energy required for dehydrogenation
 - Lower round-trip efficiency compared to physical methods
 - Carrier regeneration may need land-based infrastructure

LOHCs are especially promising for bulk transport of hydrogen to ports, onboard hotel load systems, or hybrid configurations, where their safe handling and energy buffering features are valuable.

As already mentioned, the evaluation to find out the optimal energy system configuration starts considering these three possible hydrogen storage technologies. These will be then combined with the three options for energy conversion.

In the images below, the criteria related to the hydrogen storage that have been considered in the multi-criteria analysis are reported. The bar graphs are made considering the assigned values for each criterion.

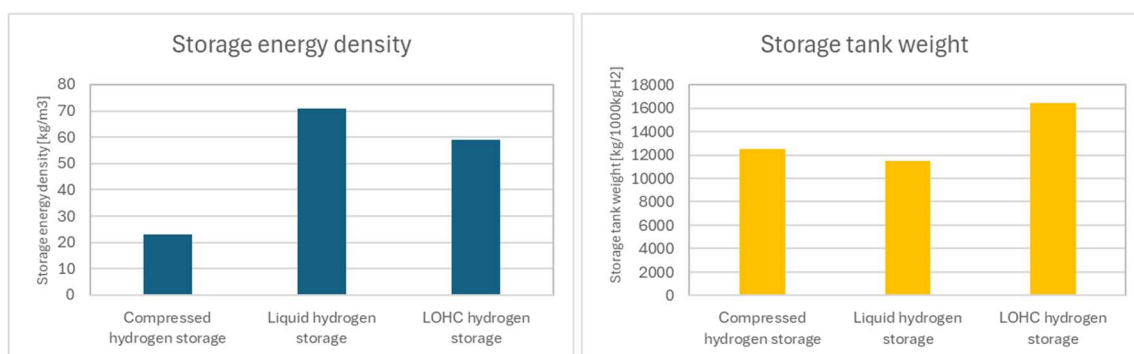


Figure 10-4 Assigned values for Storage energy density and Storage tank weight criteria

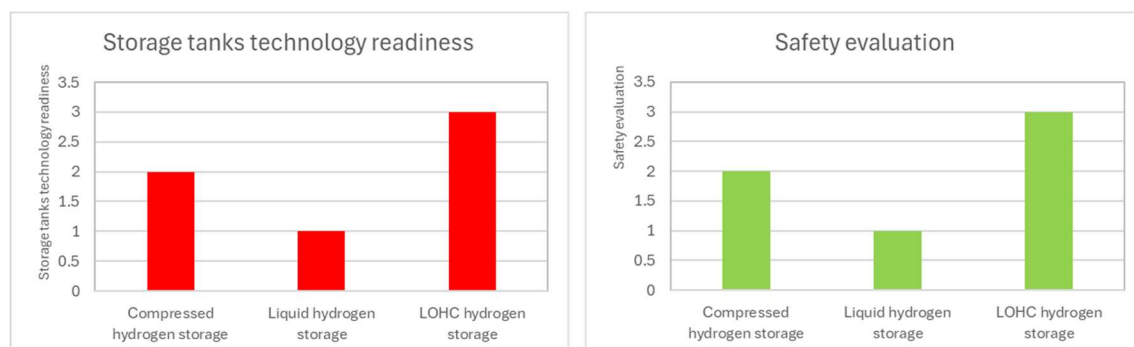


Figure 10-5 Assigned values for Storage tank readiness and safety evaluation criteria

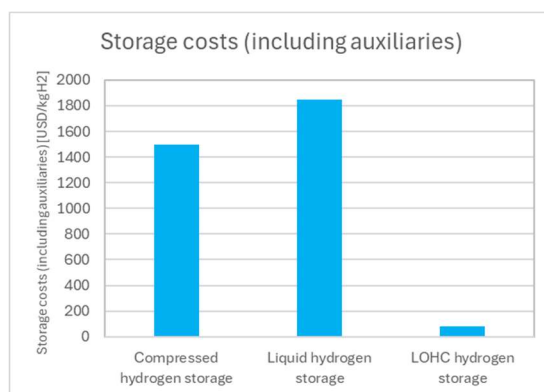


Figure 10-6 Assigned values for Storage costs criterion

Fuel Distribution System

The distribution of hydrogen from storage tanks to fuel cells or internal combustion engines requires a highly secure and efficient delivery system. Hydrogen must be supplied at the correct pressure and flow rate, with minimal energy losses during transportation. A typical fuel supply system includes high-pressure regulators, insulated transfer lines, flow control valves and leak detection sensors.

For compressed hydrogen, a cascade delivery system is often used to maintain pressure balance and prevent excessive gas expansion. Liquid hydrogen systems, on the other hand, require cryogenic transfer lines and vaporization units to convert liquid hydrogen into gaseous form before it enters the fuel cell. Given hydrogen's low molecular weight and tendency to diffuse through materials, specialized sealing technologies and reinforced piping systems are necessary to prevent leaks and ensure operational safety (Shu et al., 2022).

One of the most important aspects of hydrogen distribution is redundancy planning and safety integration. Hydrogen supply lines must be equipped with emergency shut-off valves and venting systems to allow rapid isolation in case of leaks or system failures. Explosion proof compartments and dedicated ventilation channels help prevent hydrogen accumulation in enclosed areas, reducing the risk of fire hazards (Lloyd's Register, 2023).

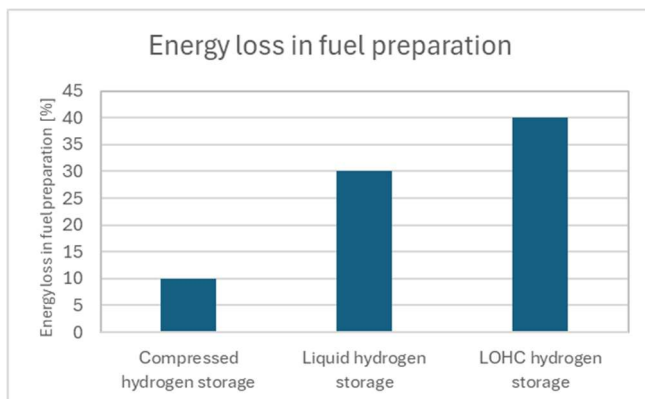


Figure 10-7 Assigned values for Energy loss in fuel preparation criterion

Additionally, integrating real-time gas monitoring sensors ensures immediate detection of any leaks, enabling automatic safety responses.

This part has been considered in the evaluation by the estimation of the energy loss for the fuel preparation.

Energy conversion

In marine applications, energy conversion systems play a crucial role in transforming hydrogen fuel into usable power for propulsion and onboard services. These systems primarily include fuel cells, such as Proton Exchange Membrane Fuel Cells (PEMFCs) and Solid Oxide Fuel Cells (SOFCs), as well

as hydrogen internal combustion engines (H_2 ICEs). Each technology offers distinct advantages in terms of efficiency, emission profiles, integration complexity, and operational dynamics. The choice between these technologies depends on multiple factors, including efficiency, emissions, scalability and compatibility with existing maritime systems.

Hydrogen-powered vessels primarily rely on two propulsion technologies: hydrogen fuel cells and hydrogen internal combustion engines (H_2 -ICE).

Proton Exchange Membrane Fuel Cells (PEMFCs) are currently the most widely adopted hydrogen power source in maritime applications due to their high efficiency and rapid response time. PEMFCs operate by converting hydrogen and oxygen into electricity through an electrochemical reaction, with water as the only by-product (Ballard Power Systems, 2023). They offer energy conversion efficiencies between 50% and 60%, significantly outperforming conventional diesel engines, which typically achieve efficiencies of only 30-40% (Wang et al., 2022). Additionally, PEMFCs provide smooth and quiet operation, reducing noise pollution. A crucial advantage for passenger ferries operating in urban and environmentally sensitive areas.

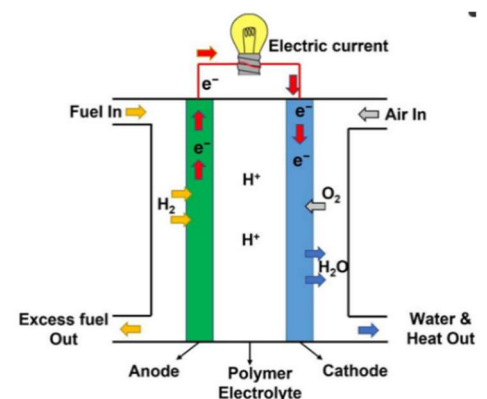


Figure 10-8 Basic schematic diagram of the PEMFC

Solid Oxide Fuel Cells (SOFCs) have also been considered for maritime applications due to their superior efficiency, reaching up to 65% (Shu et al., 2022). Unlike PEMFCs, which require high-purity hydrogen, SOFCs can utilize multiple fuels, including ammonia and methane, making them more adaptable in cases where hydrogen supply infrastructure is still under development. However, SOFCs operate at very high temperatures (typically above 700°C), requiring extensive thermal management systems and longer startup times, which limits their suitability for passenger ferries that require frequent stop-and-go operation.

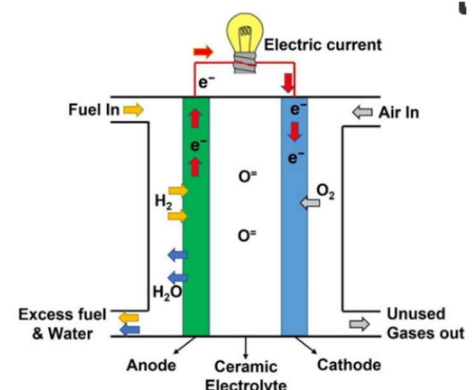


Figure 2-9 Basic schematic diagram of the SOFC

The integration of fuel cells with an energy management system (EMS) is critical for optimizing performance and fuel consumption. Advanced EMS solutions dynamically regulate power output based on real-time demand, ensuring that hydrogen is consumed efficiently while maintaining operational flexibility (Kumar et al., 2023). Fuel cells are typically coupled with lithium-ion battery

systems, which help buffer energy fluctuations and improve load management. These hybrid fuel cell-battery setups allow the fuel cells to operate at their optimal power output, extending their lifespan and reducing overall hydrogen consumption. In peak power demand scenarios, such as vessel acceleration or docking maneuvers, the battery provides supplementary power, reducing strain on the fuel cell system.

Hydrogen Internal Combustion Engines (H2-ICEs) present an alternative to fuel cells, particularly for retrofitting existing vessels. Unlike traditional marine engines, which burn fossil fuels, H2-ICEs operate by combusting hydrogen in modified diesel-cycle or spark ignition engines. The primary advantage of H2-ICEs is their compatibility with existing maritime propulsion systems, allowing for easier integration with conventional gearboxes and drivetrains.

However, H2-ICEs are less efficient than fuel cells, with an energy conversion efficiency of approximately 40%, and they can produce small amounts of nitrogen oxides (NOx) due to high combustion temperatures. Nevertheless, NOx emissions can be significantly reduced under lean-burn conditions and optimized engine operation (Verhelst et al., 2021). While NOx emissions can be mitigated through exhaust after-treatment systems, this additional complexity makes H2-ICEs less attractive for new vessel designs compared to fuel cell propulsion. The H2-ICE technology for marine application is still under development.

Thermal management is another key consideration in machinery setup. Both PEMFCs and SOFCs generate waste heat during operation, which must be effectively dissipated to maintain system efficiency and prevent overheating. PEMFC systems often incorporate liquid cooling circuits, while SOFCs require high-temperature heat exchangers and exhaust gas recirculation systems (Zhou et al., 2021). The captured waste heat from SOFCs can be repurposed for auxiliary onboard functions, such as heating and desalination, further improving overall system efficiency.

Maintenance and durability also influence the choice of machinery setup. PEMFCs require regular inspection of membrane electrode assemblies (MEAs), as degradation over time can reduce performance. The expected operational lifespan of a PEMFC in maritime applications is between 20,000 and 30,000 hours, after which stack replacement may be necessary (Ballard Power Systems, 2023). In contrast, SOFCs have longer lifespans but require specialized maintenance due to their high

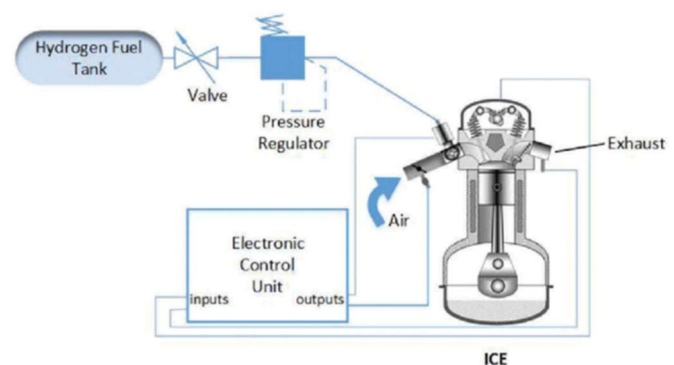


Figure 10-30 Basic schematic of H2-ICE main components

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operating temperatures and complex ceramic electrolyte structures. H2-ICE systems, while mechanically simpler, require modifications to fuel injection and combustion chamber materials to handle the unique properties of hydrogen, including its high flame speed and low energy density per unit volume.

The three above listed options have been considered in the multi-criteria analysis in combination with the already described three storage options. For their evaluation the following characteristics have been considered:

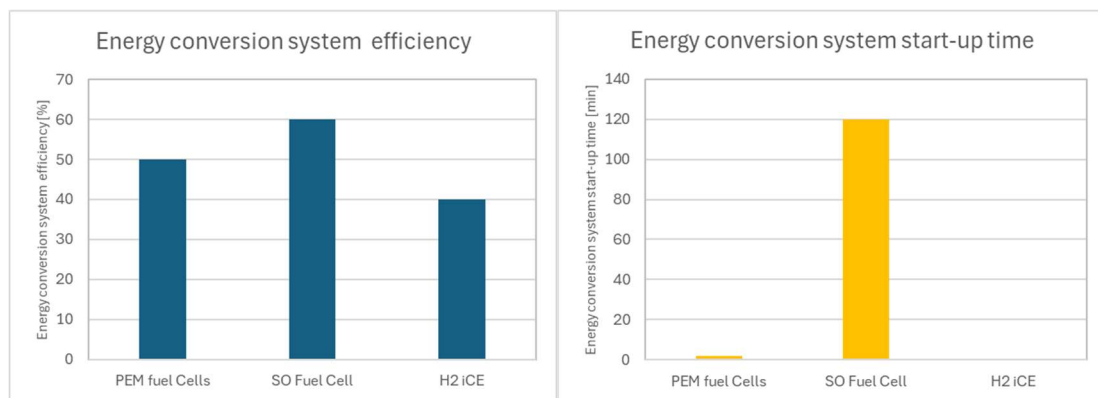


Figure 10-41 Assigned values for the Energy conversion system efficiency and Energy conversion system start-up time criteria

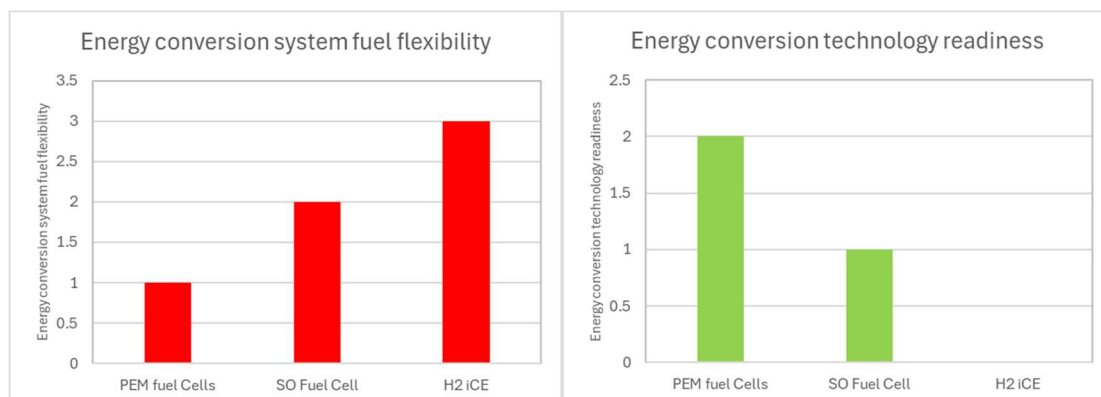


Figure 10-52 Assigned values for the Energy conversion system fuel flexibility and Energy conversion technology readiness criteria

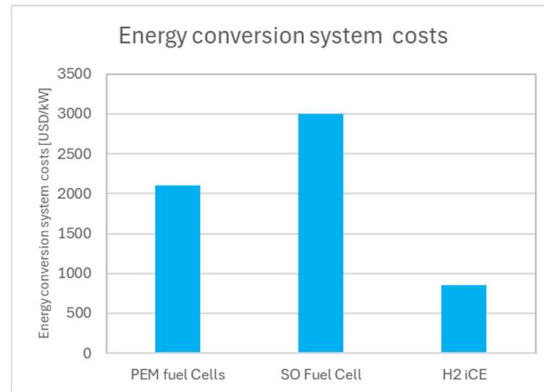


Figure 10-63 Assigned values for the Energy conversion system costs

Other aspects of the hydrogen system

The following information is provided for completeness and outlines additional aspects of the onboard hydrogen system. These elements were not included in the scope of the multicriteria analysis.

Power Conversion and Energy Management

The integration of fuel cells or hydrogen internal combustion engines, batteries and power management systems plays a crucial role in determining the overall efficiency and reliability of the hydrogen-powered vessels. The power conversion system transforms the electricity generated by fuel cells into usable power for propulsion and onboard systems. Fuel cells produce DC (direct current) electricity, which must be converted into AC (alternating current) for electric propulsion motors. A typical power conversion system includes:

- DC/DC converters to regulate fuel cell output voltage.
- DC/AC inverters for electric motor drive systems.
- Battery integration modules for hybrid energy storage.

Hybrid configurations that combine fuel cells with lithium-ion batteries allow for dynamic load balancing, ensuring that fuel cells operate at optimal efficiency while providing energy reserves for peak demand (Kumar et al., 2023). Batteries also allow regenerative energy recovery, storing excess energy generated during braking and deceleration for later use. Energy management systems (EMS) coordinate the interaction between fuel cells, batteries, and onboard electrical loads, optimizing fuel consumption and preventing overloading of any single component.

Thermal Management and Waste Heat Recovery

Both PEM fuel cells and hydrogen internal combustion engines generate excess heat that must be dissipated to maintain system stability. Effective thermal management is critical for preventing overheating and improving overall system efficiency.

- Fuel cell cooling systems typically use liquid coolant loops to regulate stack temperature and prevent thermal degradation.
- Cryogenic hydrogen storage systems require active insulation layers and vacuum jacketed piping to minimize heat ingress.
- Waste heat recovery units can capture and repurpose excess thermal energy for onboard heating, desalination, or auxiliary power generation (Zhou et al., 2021).

Solid Oxide Fuel Cells (SOFCs), which operate at temperatures above 700°C, provide opportunities for high-efficiency waste heat utilization, making them attractive for hybrid systems where residual heat can be used for secondary power applications. However, their slow startup time limits their applicability in passenger ferries requiring rapid deployment.

Safety and Regulatory Considerations

Ensuring compliance with IMO, SOLAS and classification society standards is a fundamental requirement for the implementation of hydrogen-based energy systems. The IGF Code (International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels) provides guidelines for hydrogen handling, storage and system integration (Lloyd's Register, 2023). Key safety measures include:

- Dedicated hydrogen storage compartments with fireproof barriers.
- Automated hydrogen leak detection and emergency shutdown systems.
- Controlled venting systems to prevent gas accumulation.
- Explosion-proof electrical components.

Additionally, classification societies such as Lloyd's Register and DNV have developed specific guidelines for hydrogen-powered ships, outlining best practices for tank placement, fire suppression, and explosion-proof enclosures (Lloyd's Register, 2023). Compliance with these regulations is essential for ensuring the safe operation of hydrogen vessels in commercial service.

To further enhance safety, crew training programs and emergency response protocols must be implemented to ensure operators are equipped to handle hydrogen-related incidents effectively.

Propulsion architectures

Hydrogen-fueled vessels can adopt either a fully electric propulsion system, where fuel cells generate electricity for electric motors, or a hybrid system that combines fuel cells with batteries to optimize



power delivery. Fully electric propulsion offers simplicity and reliability, with fewer mechanical components and reduced maintenance requirements compared to internal combustion-based systems (Kumar et al., 2023). However, integrating battery storage with fuel cells enhances system efficiency by allowing load balancing and peak shaving, reducing hydrogen consumption and extending fuel cell lifespan. Hybrid architectures also enable regenerative energy recovery, particularly useful for ferries operating in regions with frequent stop-and-go operations, such as urban waterways.

Battery-assisted propulsion also enables regenerative braking in certain vessel designs, capturing excess energy during deceleration and feeding it back into the system. This feature is particularly useful for ferries operating on short, frequent routes where docking and undocking cycles occur multiple times per hour. Additionally, batteries provide a redundant energy source, ensuring that the vessel can operate temporarily on stored energy if there is an issue with the hydrogen supply or fuel cell system.

One challenge of hybrid architectures is the added weight and volume of battery storage. Unlike fuel cells, which continuously generate power as long as hydrogen is available, batteries require additional space for installation, increasing the vessel's displacement. However, advancements in solid-state battery technology and high-density energy storage solutions are addressing these limitations, making hybrid fuel cell-battery configurations increasingly viable for passenger ferries (Zhou et al., 2021).

Hydrogen refuelling infrastructure

The integration of hydrogen refueling infrastructure is another essential factor in determining the feasibility of hydrogen-fueled ships. Ports must be equipped with hydrogen storage, compression, and dispensing systems capable of refueling vessels efficiently while adhering to safety regulations. Studies have shown that a lack of refueling infrastructure remains one of the primary barriers to hydrogen adoption in the maritime sector (Verma et al., 2023). In response, initiatives such as the European H2Ports project and the Clean Hydrogen Alliance are working to develop port-based hydrogen supply chains that can support the widespread deployment of hydrogen-powered vessels.

The optimal energy system layout for hydrogen-powered passenger ferries depends on multiple factors, including storage method, power conversion strategy and thermal management.

The next section will explore multicriteria analysis technique used to evaluate different configurations, comparing economic, environmental and technical performance factors to determine the most viable hydrogen-powered passenger ferry solutions.

6. Multicriteria Analysis

The selection of an optimal hydrogen-fueled propulsion configuration for passenger vessels requires a systematic and quantitative evaluation of multiple factors, balancing technical feasibility, economic viability, environmental impact and regulatory compliance. Given the complexity of hydrogen propulsion systems, a Multicriteria Decision Analysis (MCDA) approach is employed to assess different configurations against key performance indicators. This methodology allows decision-makers to compare trade-offs between various hydrogen-based technologies and select the most suitable option based on operational, economic and environmental priorities.

Methodological Approach

Multicriteria Decision Analysis (MCDA) is a structured framework used to evaluate complex systems where multiple objectives must be considered simultaneously. The MCDA process involves:

1. Defining evaluation criteria based on technical, economic, environmental and safety parameters.
2. Identifying candidate propulsion configurations, including different energy conversion systems (PEMFCs, SOFCs and H2ICE) and different hydrogen storage options (compressed hydrogen, liquid hydrogen, LOHC).
3. Assigning weight factors to each evaluation criterion based on stakeholder priorities and industry benchmarks.
4. Scoring each alternative according to how well it meets the defined criteria.
5. Applying decision-making models, such as Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), to rank and select the best configuration.

This structured evaluation ensures that the chosen hydrogen propulsion system aligns with both short-term feasibility and long-term sustainability goals in maritime transport.

Evaluation Criteria

To comprehensively assess different hydrogen propulsion configurations, the following three primary evaluation categories are considered:

1. Technical Performance

- Storage system energy density: Indication of how many kilograms of hydrogen can be stored in 1 m³.
- Storage tank weight: Added weight in kg to store 1000 kg of hydrogen

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- Energy conversion system efficiency: Fuel-to-power conversion efficiency, including losses in fuel cells or combustion engines.
- Energy loss in fuel preparation: includes losses for heating and evaporation of liquid hydrogen, dehydrogenation for the LOHC, etc
- Energy conversion system start-up time: estimated time for the readiness of the system
- Energy conversion system fuel flexibility: ranking of the three conversion systems
- Energy conversion system readiness: estimation of the technology readiness to be used for an installation on board
- Storage tanks technology readiness: estimation of the technology readiness to be used for an installation on board

2. Economic Feasibility

- Storage system CAPEX cost (including auxiliaries) [USD/kWh]
- Energy conversion system CAPEX cost [USD/kWh]

3. Environmental Impact

- Air quality impact: Emission of nitrogen oxides (NO_x) from H₂-ICE systems versus zero-emission fuel cells.

4. Regulatory and Safety Compliance

- Safety considerations: Risk of hydrogen leaks, explosion-proof storage requirements and emergency response protocols.
- Infrastructure readiness: Availability of port-side refueling and storage infrastructure.

Comparison of Hydrogen Propulsion Configurations

Using the defined evaluation criteria, nine primary hydrogen propulsion configurations are assessed:

1. PEM FCs with compressed hydrogen storage

- Pros: High efficiency (50-60%), zero emissions, quiet operation, and modular scalability, low energy loss for fuel preparation.
- Cons: High initial CAPEX, limited hydrogen refueling infrastructure, low energy storage density and sensitivity to hydrogen purity.

2. PEM FCs with liquid hydrogen storage

- Pros: High efficiency (50-60%), zero emissions, quiet operation and modular scalability.
- Cons: High initial CAPEX, limited hydrogen refueling infrastructure, and sensitivity to hydrogen purity, high energy loss for fuel preparation, boil-off gas management.

3. PEM FCs with LOHC hydrogen storage

- Pros: High efficiency (50-60%), zero emissions, quiet operation, modular scalability, high storage technology readiness, very low storage cost, high safety
- Cons: High initial CAPEX and sensitivity to hydrogen purity, very high energy loss for fuel preparation.

4. SOFCs with compressed hydrogen storage

- Pros: Very high efficiency (60%), zero emissions, quiet operation, modular scalability, low energy loss for fuel preparation, low sensitivity on hydrogen purity
- Cons: High initial CAPEX, low energy storage density, limited hydrogen refueling infrastructure, long start-up time

5. SOFCs with liquid hydrogen storage

- Pros: Very high efficiency (60%), zero emissions, quiet operation, modular scalability, low sensitivity on hydrogen purity, high energy storage density
- Cons: High initial CAPEX, limited hydrogen refueling infrastructure, long start-up time, high energy loss for fuel preparation, boil-off gas management

6. SOFCs with LOHC hydrogen storage

- Pros: Very high efficiency (60%), zero emissions, quiet operation, modular scalability, low sensitivity on hydrogen purity, high storage technology readiness, very low storage cost, high safety
- Cons: High initial CAPEX, long start-up time, very high energy loss for fuel preparation

7. H2-ICEs with compressed hydrogen storage

- Pros: Compatibility with existing propulsion systems, relatively lower CAPEX, faster refueling, low energy loss for fuel preparation, low sensitivity on hydrogen purity
- Cons: Low efficiency (~40%), low energy storage density, limited hydrogen refueling infrastructure, NO_x emissions

8. H2-ICEs with liquid hydrogen storage

- Pros: Compatibility with existing propulsion systems, relatively lower CAPEX, low sensitivity on hydrogen purity, high energy storage density



- Cons: Low efficiency (~40%), high energy loss for fuel preparation, boil-off gas management, limited hydrogen refueling infrastructure, NO_x emissions

9. H2-ICEs with LOHC hydrogen storage

- Pros: Compatibility with existing propulsion systems, relatively lower CAPEX, low sensitivity on hydrogen purity, high storage technology readiness, very low storage cost, high safety
- Cons: Low efficiency (~40%), very high energy loss for fuel preparation, NO_x emissions

Methodology of multi-criteria assessment

The objective of the assessment is to identify, among a set of m feasible technical solutions for hydrogen-fuelled vessels operating on a specific route, the most promising option from technical, environmental and economic standpoints. Each of these dimensions requires distinct performance criteria, which often conflict with one another. Therefore, it is necessary to analyze the candidate options through these three lenses, define appropriate performance indicators and use them to enable a comparative evaluation.

Multi-Criteria Decision Analysis (MCDA) provides a structured framework to support this process. MCDA allows decision-makers to evaluate and prioritize alternatives by considering multiple and often conflicting criteria simultaneously. This approach is especially valuable in complex decision-making contexts, such as the maritime energy transition, where balancing technical performance, environmental impact and cost-effectiveness is essential.

At the core of MCDA is the performance matrix (also known as the decision matrix), which organizes the available options (typically as rows) against the selected evaluation criteria (as columns). Each cell of the matrix contains the performance value x_{ij} of option (i) with respect to criterion (j), expressed in the original measurement scale of that criterion. This matrix forms the basis for applying various MCDA methods, which are then used to compare, assess and in many cases, rank the alternatives according to their multi-dimensional performance.

This activity aims to evaluate all the options and building a final ranking of them in order to determine the one that has the most effective overall performance. As for the Activity 2.1, it was decided to use

a well- established method that has frequently been used in technical or engineering problems²: the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution³) method.

The TOPSIS method is a widely adopted Multi-Criteria Decision Analysis (MCDA) technique used to rank alternatives based on their relative closeness to an ideal solution. It is particularly well-suited for decision-making contexts involving multiple, and potentially conflicting, criteria. The core principle of TOPSIS is that the optimal alternative should have the shortest distance from the ideal solution and the farthest distance from the anti-ideal (or worst-case) solution.

The application of the TOPSIS method involves several key steps. First, a performance matrix is constructed, in which each element represents the performance of a given alternative with respect to a specific criterion. This step requires a clear definition of the alternatives (options) under evaluation and the criteria against which they are assessed.

Option	Description	Storage energy density [kg/m ³] (2)	Added weight for storage of 1t of hydrogen [kg]	Energy conversion system efficiency [%] (5)	Energy loss in fuel preparation [%] (6)	Energy conversion system start-up time [min]	Energy conversion system fuel flexibility	Energy conversion technology readiness	Storage tanks technology readiness	Storage costs (including auxiliaries) [USD/kg H ₂] (3)	Energy conversion system costs [USD/kW] (1)	NO _x production [g/kWh] (4)	Safety
1	PEMFCs with compressed H ₂ (350 bar)	23	12500	50	10	2	1	2	2	1500	2100	0	2
2	PEMFCs with liquid H ₂	70.8	12000	50	30	2	1	2	1	1850	2100	0	1
3	PEMFCs with LOHC	59	17000	50	45	2	1	2	2	1200	2100	0	3
4	SOFCs with compressed H ₂ (350 bar)	23	12500	60	10	120	2	1	2	1500	3000	0	2
5	SOFCs with liquid H ₂	70.8	12000	60	30	120	2	1	1	1850	3000	0	1
6	SOFCs with LOHC	59	17000	60	45	120	2	1	2	1200	3000	0	3
7	H ₂ -ICE with compressed H ₂ (350 bar)	23	12500	40	10	0.5	3	0	2	1500	850	0.12	2
8	H ₂ -ICE with liquid H ₂	70.8	12000	40	30	0.5	3	0	1	1850	850	0.12	1
9	H ₂ -ICE with LOHC	59	17000	40	45	0.5	3	0	2	1200	850	0.12	3

Figure 11-7 Performance matrix

DATA SOURCES:

- (1) Fredrik G.Aarskog, Janis Danebergs, Trond Stromgren and Oystein Ulleberg, Energy and cost analysis of a hydrogen driven high speed passenger ferry, 21 April 2020 Sustainability whitepaper, HYDROGEN AS MARINE FUEL, June 2021
- (2) ABS, Sustainability whitepaper, Hydrogen as Marine Fuel, June 2021
- (3) Fredrik G.Aarskog, Janis Danebergs, Trond Stromgren and Oystein Ulleberg, Energy and cost analysis of a hydrogen driven high speed passenger ferry, 21 April 2020 Sustainability whitepaper, HYDROGEN AS MARINE FUEL, June 2021 EU co-funded Shyps project data, 2025 BNEF Hydrogen Economy Outlook Key Messages 30 March 2020. 2020. Available (estimation by JPMorgan)
- (4) Energy Homeland security, The future of H₂ internal combustion engines in California

² For a recent review, see: Pandey, V., Komal, & Dincer, H. (2023). A review on TOPSIS method and its extensions for different applications with recent development. *Soft Computing*, 27(23), 18011-18039.

³ Hwang, C.-L., & Yoon, K. (1981). Multiple Attribute Decision Making: Methods and Applications: a State-of-the-art Survey (p. 259). Springer-Verlag.

(5) Energy Homeland security, The future of H2 internal combustion engines in California EU co-funded sHYpS Project, 2025

(6) Estimated from literature

(7) Qian Cheng, Ruiqiang Zhang, Zhusheng Shi, Jianguo Lin, Review of common hydrogen storage tanks and current manufacturing methods for aluminium alloy tank liners

Since the performance values are often expressed in diverse units and scales, the next step is the normalization of the matrix. This process standardizes the data, ensuring that all criteria are converted into a dimensionless, comparable form, which is essential for subsequent distance calculations. This is typically done using vector normalization; if x_{ij} is the value of the performance of option (i) in criterion (j) before the normalisation, the normalised value r_{ij} is:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_i x_{ij}^2}}$$

The normalised performance matrix includes all the normalised values.

The third step in the TOPSIS method involves incorporating the relative importance of each criterion through the assignment of weights. This allows decision-makers to reflect the varying significance of the criteria in the context of the specific decision problem. Each criterion is assigned a weight, and the normalized performance matrix is then multiplied by these weights to produce the weighted normalized performance matrix, where each element is denoted as v_{ij} .

In the case of the TransH2 project, it was decided to apply equal weights to all criteria, reflecting a uniform level of importance. Under equal weighting, the transformation results in a scaled version of the normalized matrix, preserving the relative performance values. This ensures that the sum of the weighted values for any given alternative does not exceed 1, maintaining consistency and comparability across the dataset.

The fourth step involves identifying the ideal (best) and anti-ideal (worst) solutions. These reference points do not correspond to actual alternatives but are instead hypothetical constructs derived from the performance of the available options. Each alternative is represented by a vector of weighted normalized performance values $[v_{ij}, j=1, \dots, n]$, where n is the number of criteria.

To define the ideal solution, the best performance values are selected across all criteria: maximum values for benefit criteria (where higher values are preferred) and minimum values for cost criteria (where lower values are preferred). Conversely, the anti-ideal solution consists of the minimum values for benefit criteria and maximum values for cost criteria. These two constructed vectors

represent the benchmark extremes against which all actual alternatives are evaluated in subsequent steps of the TOPSIS method.

Option	Description	Storage energy density [kg/m ³]	Added weight for storage of 1t of hydrogen [kg]	Energy conversion system efficiency [%]	Fuel preparation efficiency	Energy conversion system start-up time	Energy conversion fuel flexibility	Energy conversion technology readiness	Storage tanks technology readiness	Storage costs [USD/kg H ₂]	Energy conversion system costs	NO _x production	Safety
1	PEMFCs with compressed H ₂ (350 bar)	0.047	0.099	0.110	0.035	0.003	0.051	0.172	0.128	0.108	0.108	0.000	0.103
2	PEMFCs with liquid H ₂	0.143	0.095	0.110	0.105	0.003	0.051	0.172	0.064	0.133	0.108	0.000	0.051
3	PEMFCs with LOHC	0.120	0.135	0.110	0.157	0.003	0.051	0.172	0.128	0.087	0.108	0.000	0.154
4	SOFCS with compressed H ₂ (350 bar)	0.047	0.099	0.132	0.035	0.192	0.103	0.086	0.128	0.108	0.154	0.000	0.103
5	SOFCS with liquid H ₂	0.143	0.095	0.132	0.105	0.192	0.103	0.086	0.064	0.133	0.154	0.000	0.051
6	SOFCS with LOHC	0.120	0.135	0.132	0.157	0.192	0.103	0.086	0.128	0.087	0.154	0.000	0.154
7	H ₂ -ICE with compressed H ₂ (350 bar)	0.047	0.099	0.088	0.035	0.001	0.154	0.000	0.128	0.108	0.044	0.192	0.103
8	H ₂ -ICE with liquid H ₂	0.143	0.095	0.088	0.105	0.001	0.154	0.000	0.064	0.133	0.044	0.192	0.051
9	H ₂ -ICE with LOHC	0.120	0.135	0.088	0.157	0.001	0.154	0.000	0.128	0.087	0.044	0.192	0.154
v _j [*]	Best combination	0.143	0.095	0.132	0.035	0.003	0.103	0.172	0.128	0.087	0.044	0.000	0.154
v _j [*]	Worst combination	0.047	0.135	0.088	0.157	0.192	0.051	0.000	0.128	0.133	0.154	0.192	0.051

Figure 11-8 Weighted performance matrix

The fifth step is the calculation of the Euclidean distance of each alternative from the ideal and anti-ideal solutions (separation measures). For instance, if [v_j^{*}] is the vector that represents the ideal solution, then the separation measure of option (i) from the ideal solution (D_i^{*}) is

$$D_i^* = \sqrt{\sum_j (v_{ij} - v_j^*)^2}$$

Similarly, the separation measure from the anti-ideal solution (D_i⁻) is calculated for all options.

Each alternative *i* is subsequently characterized by two key metrics: its distance from the ideal solution and its distance from the anti-ideal solution. It is important to emphasize that relying solely on one of these separation measures is insufficient for effective ranking. An option that is closest to the ideal solution may not necessarily be the farthest from the anti-ideal, and vice versa. Therefore, the sixth step involves computing a relative closeness coefficient to the ideal solution, denoted as C_i^{*}, which integrates both separation measures to determine the overall desirability of each alternative.

$$C_i^* = \frac{D_i^-}{D_i^* + D_i^-}$$

The coefficient C_i^* ranges between 0 and 1, where a value of 0 indicates that option i coincides with the anti-ideal solution and a value of 1 signifies that it matches the ideal solution. This coefficient serves as a basis for ranking the alternatives, with higher values representing options that are more closely aligned with the ideal, and lower values indicating those closer to the worst-case scenario.

Results of the multicriteria assessment

By applying the above procedure, the overall performance of the options are:

Option	Description	D ⁺	D ⁻	C [*]
1	PEMFCs with compressed H ₂ (350 bar)	0.140	0.353	0.715
2	PEMFCs with liquid H ₂	0.170	0.351	0.673
3	PEMFCs with LOHC	0.156	0.374	0.705
4	SOFCs with compressed H ₂ (350 bar)	0.260	0.292	0.528
5	SOFCs with liquid H ₂	0.278	0.259	0.482
6	SOFCs with LOHC	0.269	0.289	0.518
7	H ₂ -ICE with compressed H ₂ (350 bar)	0.289	0.309	0.516
8	H ₂ -ICE with liquid H ₂	0.305	0.278	0.477
9	H ₂ -ICE with LOHC	0.297	0.307	0.508

Figure 11-9 Measures of overall performance of the option

So the final ranking of the technical options are:

Ranking position	Option n°	Description	Coefficient of similarity
1	1	PEMFCs with compressed H ₂ (350 bar)	0.715
2	3	PEMFCs with LOHC	0.705
3	2	PEMFCs with liquid H ₂	0.673
4	4	SOFCs with compressed H ₂ (350 bar)	0.528
5	6	SOFCs with LOHC	0.518
6	7	H ₂ -ICE with compressed H ₂ (350 bar)	0.516
7	9	H ₂ -ICE with LOHC	0.508
8	5	SOFCs with liquid H ₂	0.482
9	8	H ₂ -ICE with liquid H ₂	0.477

Figure 11-10 Final ranking of the technical options

Italy – Croatia



TransH2

The ranking highlights the superior performance of PEM fuel cell (PEMFC) systems, which occupy the top three positions across all storage technologies considered. **The highest-ranked configuration is PEMFC with compressed hydrogen at 350 bar (Option 1)**, achieving the greatest similarity to the ideal solution with a coefficient of 0.715. This reflects a strong balance across technical, economic and environmental criteria, likely due to its maturity, efficiency and compatibility with existing refueling infrastructure.

Closely following are PEMFCs with LOHC (Option 3) and with liquid hydrogen (Option 2), scoring 0.705 and 0.673, respectively. Their proximity to the top option confirms the robustness of PEMFC technology across different hydrogen storage strategies.

Solid Oxide Fuel Cells (SOFCs) rank in the mid-tier, with compressed hydrogen performing slightly better than LOHC and liquid H₂. SOFCs generally provide higher efficiency at steady state but may have been penalized in this evaluation due to lower technology readiness and slower dynamic response, both of which are critical for marine applications.

Hydrogen Internal Combustion Engines (H₂-ICE) consistently rank in the lower tier, with the lowest coefficient of 0.477 for H₂-ICE with liquid hydrogen. While H₂-ICE technology benefits from simplicity and mechanical familiarity, its lower efficiency, higher NO_x emissions, and mechanical complexity likely contributed to its weaker performance in this multicriteria context.

The best configuration that emerges from the multi-criteria analysis, which includes compressed hydrogen storage and a PEM fuel cell, will be implemented on both vessels operating along regional and international routes. As previously outlined in Activity 2.1, the key difference lies in the vessels' endurance when operating on hydrogen. The concept for regional routes envisions a fully hydrogen-powered vessel, whereas the design for international routes will adopt a hybrid solution, with hydrogen propulsion limited to port operations.

7. General recommendations for the hydrogen implementation on board

Hydrogen Storage and Containment Safety

Given hydrogen's high flammability and low molecular weight, proper containment and ventilation are essential for preventing leaks and ensuring safe fuel storage. The main storage options, compressed hydrogen (CH₂) and liquid hydrogen (LH₂), present different safety challenges. To mitigate risks the following indications should be considered:

- Tanks must be placed in designated explosion-proof compartments, separate from passenger areas.
- Overpressure relief valves and automatic shutdown systems must be installed to prevent uncontrolled hydrogen release.
- Leak detection sensors and ventilation ducts should be incorporated to remove any leaked hydrogen before it accumulates in enclosed spaces.
- Liquid Hydrogen (LH₂) Safety Measures: LH₂ storage introduces additional safety considerations due to cryogenic temperatures (-253°C) and boil-off gas (BOG) management:
 - Tanks must be thermally insulated with multilayer vacuum insulation to prevent heat ingress and minimize evaporation losses.
 - Boil-off gas must be safely vented or re-liquefied to avoid pressure buildup in the storage tanks.
 - Cryogenic fuel transfer lines must be reinforced to prevent thermal stress fractures and leaks.

Both CH₂ and LH₂ storage solutions must adhere to IMO and classification society requirements, ensuring safe handling and operational reliability under maritime conditions.

Fire and Explosion Risk Mitigation

Hydrogen is highly flammable, requiring specialized fire protection systems to prevent thermal runaway, combustion, or explosion risks. The primary fire suppression strategies should include:

- Fire-Resistant Hydrogen Compartments: Fuel storage areas must be enclosed within fire-resistant compartments to prevent direct exposure to ignition sources. Materials used must comply with fire protection standards (IMO MSC.1/Circ.1558) to withstand extreme conditions.



- Inert Gas Purging Systems: To prevent hydrogen build-up, inert gases such as nitrogen can be used to purge fuel lines and storage tanks, reducing the risk of combustion.
- Explosion-Proof Electrical Components: All electrical circuits, sensors and control systems in hydrogen-prone areas must be explosion-proof to prevent accidental ignition.
- Automatic Leak Detection and Ventilation: Hydrogen sensors must be installed throughout the vessel to detect leaks in real time. Upon detection, automated ventilation systems should immediately activate to disperse hydrogen gas safely into the atmosphere (DNV, 2023).
- Hydrogen Flame Detectors: Unlike conventional fuels, hydrogen burns with an invisible flame, making infrared or ultraviolet flame detection systems essential for rapid fire response.

Crew Training and Emergency Response

Proper training for ferry operators and emergency responders is crucial for safely managing hydrogen-powered vessels. IMO regulations mandate that crews receive specialized training on handling alternative fuels, with specific focus on:

- Hydrogen Fuel Handling Procedures: Training on safe refueling, leak prevention and emergency shutdown protocols.
- Fire Suppression Drills: Crews must be trained to respond to hydrogen-related fire scenarios, including deployment of fire suppression agents and evacuation procedures.
- System Failure Simulations: Regular testing of fuel cell shutdown procedures, battery management systems and emergency power backups to ensure vessel operability during technical failures.

Hydrogen-powered vessels must also coordinate with port authorities, firefighters and coast guard units to ensure emergency response teams are equipped to handle hydrogen related incidents.

Regulatory Challenges and Future Outlook

Despite the existence of IMO, SOLAS and classification society guidelines, regulatory frameworks for hydrogen propulsion remain in the early stages of development. Several challenges must still be addressed to facilitate large-scale deployment:

- Lack of specific IMO rules for hydrogen ships: While the IGF Code provides general provisions for low-flashpoint fuels, additional amendments are needed to fully incorporate hydrogen-specific safety standards.
- Hydrogen refueling infrastructure gaps: Ports require specialized hydrogen refueling stations, but few global ports currently meet IMO safety standards for on-site hydrogen handling and bunkering (European Maritime Safety Agency, 2023).

Italy – Croatia



TransH2

- Standardization of hydrogen storage technologies: CH₂ and LH₂ storage solutions must be standardized across vessel types to streamline refueling operations and regulatory compliance.

To address these challenges, industry collaborations and research initiatives are actively working to refine hydrogen safety guidelines. The European H2Ports Project and the Clean Hydrogen Alliance are developing port safety protocols, while classification societies are updating technical standards for hydrogen vessel designs.

As regulatory frameworks continue to evolve, collaboration between governments, classification societies and maritime stakeholders will be critical in establishing a globally standardized hydrogen safety framework. The future of hydrogen-powered vessels will depend on the harmonization of safety regulations, port infrastructure expansion and continuous innovation in fuel storage and fire prevention technologies.

Vessel design

This section focuses on recommendations for optimizing hydrogen vessel designs, outlining best practices for implementing next-generation propulsion systems in passenger ferries.

Optimal Hydrogen Propulsion Configuration

The PEM FC and gaseous hydrogen storage emerges as the most viable configuration for hydrogen powered passenger ferries.

The combination with a battery systems (Lithium-ion battery storage) should be incorporated to buffer peak loads, improve fuel cell lifespan and enable regenerative braking during docking and deceleration.

Multi-stack fuel cell configurations should be adopted to ensure modular power generation, allowing for individual stack shutdowns without disrupting operations.

Advanced Energy Management Systems (EMS) should be implemented to optimize fuel cell-battery interaction and improve overall efficiency.

Hydrogen Storage and Refueling Strategy

Hydrogen bunkering facilities must be developed at major ferry ports, with a focus on on-site hydrogen production from renewable energy sources. Investments in port-side hydrogen compression, liquefaction and distribution pipelines will be essential for long-term adoption.

Vessel Design and Energy System Optimization

Italy – Croatia



TransH2

The integration of hydrogen fuel systems into ferry designs must consider space constraints, weight distribution and safety requirements.

- Hydrogen storage tanks should be positioned below deck or within dedicated fire-resistant compartments to improve vessel stability. Lightweight composite materials should be used to offset the additional weight of fuel cell stacks and storage systems.
- Waste heat recovery systems should be integrated for repurposing excess thermal energy for onboard use.
- Automated Leak Detection and Ventilation: To ensure operational safety, hydrogen powered ferries must include real-time gas monitoring sensors, automatic ventilation systems, and emergency shutdown mechanisms.

Regulatory Compliance and Safety Enhancements

Ensuring compliance with IMO, SOLAS, and classification society regulations is critical for the safe operation of hydrogen-powered ferries.

- Implementation of IMO IGF Code Requirements: Hydrogen storage and fuel handling must comply with explosion-proof enclosure standards, controlled venting systems, and fire suppression regulations.
- Crew Training and Safety Protocols: Ferry operators must undergo specialized training in hydrogen fuel handling, emergency response, and refueling procedures.

Regular safety drills should be conducted to simulate fire suppression and leak containment scenarios.

Scalability and Future-Proofing

To ensure long-term sustainability, hydrogen-powered ferries must be designed with future scalability in mind.

- Standardization of Hydrogen Systems: Common fuel cell sizes, hydrogen tank configurations, and refueling protocols should be adopted to streamline vessel manufacturing and refueling operations.
- Integration with Green Hydrogen Production: Ferry operators should invest in renewable hydrogen sourcing, leveraging wind, solar, and hydropower electrolysis to ensure 100% carbon-free operations.

Hydrogen-powered passenger ferries represent the next frontier in zero-emission maritime transport, offering a clean, efficient and sustainable alternative to diesel-based propulsion. By adopting fuel cell-battery hybrid systems, investing in hydrogen refueling infrastructure and ensuring

Italy – Croatia



compliance with stringent safety standards, the maritime industry can accelerate the transition toward decarbonized sea mobility.

Policymakers, shipbuilders, and ferry operators must work collaboratively to expand hydrogen availability, lower costs and refine safety regulations. As technology matures and economies of scale improve, hydrogen ferries will become an integral part of sustainable maritime networks, supporting climate goals and green transportation initiatives worldwide.

8. Conclusions on the optimal configuration selection

The transition to hydrogen-fueled passenger ferries represents a paradigm shift in maritime transportation, offering a zero-emission alternative to conventional fossil-fuel powered vessels. This report has provided a comprehensive analysis of the technical, economic, environmental and regulatory factors influencing the adoption of hydrogen propulsion for ferry services. Through an in-depth assessment of fuel cell technology, propulsion architectures, energy system layouts, and safety aspects considerations, it has become evident that hydrogen has the potential to reshape the maritime sector, aligning with international decarbonization goals such as those set by the International Maritime Organization (IMO) and the European Green Deal.

The multi-criteria analysis performed clearly shows that PEM fuel cell (PEMFC) systems outperform other technologies, with the top three positions across all storage methods. The best-performing configuration is PEMFC with compressed hydrogen (350 bar), followed closely by PEMFC with LOHC and liquid hydrogen. This reflects the maturity, efficiency, and integration flexibility of PEMFCs in marine applications.

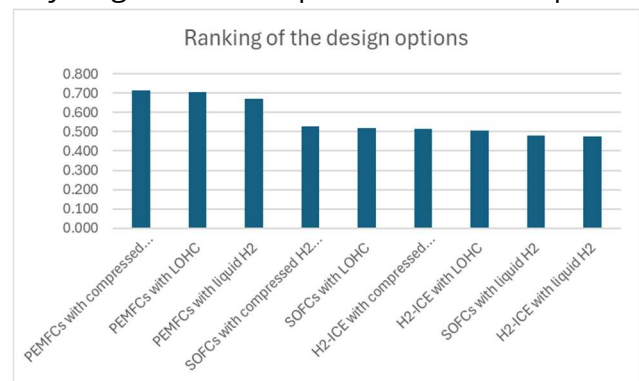


Figure 12-11 Ranking of the evaluated design options

SOFCs rank in the middle, showing moderate performance, likely limited by lower readiness and slower dynamics. Hydrogen ICEs consistently rank lowest, mainly due to lower efficiency, emissions concerns and technology readiness.

Overall, PEMFCs combined with compressed H₂ present the most balanced and effective solution among the options evaluated.

A critical barrier to widespread hydrogen adoption remains the lack of refueling infrastructure and the high cost of hydrogen production. While green hydrogen produced via electrolysis provides a fully carbon-free energy source, current production capacity and distribution networks remain limited and expensive. Public-private partnerships, government subsidies and investments in hydrogen supply chains will be essential to overcoming these challenges. Hydrogen-fueled ferries will only achieve full market competitiveness if supported by a scalable refueling ecosystem and cost reductions through economies of scale.

Safety and regulatory compliance are paramount in the deployment of hydrogen-powered vessels. Hydrogen's flammability, low ignition energy, and rapid diffusion properties require advanced leak

Italy – Croatia

**TransH2**

detection systems, explosion-proof enclosures, and emergency response protocols. International regulations such as the IMO IGF Code, SOLAS, and classification society guidelines provide a framework for safe hydrogen fuel handling, but additional standardization efforts and regulatory updates will be necessary to fully accommodate hydrogen as a mainstream maritime fuel.

Moving forward, it is imperative that ferry operators, policymakers, shipbuilders, and hydrogen producers collaborate to establish a well-defined roadmap for hydrogen adoption in maritime transport. Investment in green hydrogen production, regulatory support for port infrastructure upgrades and continued advancements in fuel cell efficiency will dictate the pace of hydrogen integration in the sector.

In conclusion, hydrogen-powered passenger ferries present a transformative opportunity for the maritime industry, offering an efficient, scalable, and truly zero-emission alternative to traditional fuel sources. As regulations tighten, hydrogen technology matures and the economic case for clean shipping strengthens, hydrogen will play a crucial role in the future of sustainable maritime transport.

9. Route selection for hydrogen powered passenger vessels

Environmental evaluation

The environmental evaluation conducted within the project primarily focuses on assessing (i) the air quality in areas of interest, such as the involved ports and routes trajectories, (ii) the protected natural areas that are within the route area, and (iii) the CO₂ equivalent emissions avoidance. For what concerns the last point, the CO₂ equivalent emissions avoidance will be analysed in the sections dedicated to the transportation analysis of each selected maritime route.

Air quality

Air pollution is considered nowadays as the most significant environmental threat to human health and is recognized as the second-largest environmental concern among Europeans, following climate change. The unfavourable effects of poor air quality (such as respiratory and cardiovascular diseases, asthma, and allergies) are observed as critical issues by European citizens. Consequently, air quality has acquired increased political, media, and public attention, accompanied by growing support for measures to address the problem⁴.

Generally, an air quality assessment is a process used to evaluate the concentration of pollutants in the atmosphere, their potential sources, and their impact on human health, ecosystems, and the climate. However, this report focuses on solely evaluating the concentration of key pollutants in the areas related to the three selected maritime routes. Such an evaluation is crucial for understanding environmental conditions in the areas of interest and implementing measures to improve air quality.

A typical air quality evaluation focuses on a range of chemical parameters that influence the environment and hence the public health. These parameters generally include (typically measured in micrograms per cubic meter (µg/m³) of air, except for the Carbon Monoxide, which is usually measured in milligrams per cubic meter (mg/m³) of air):

- **Particulate Matter (PM)** consists of a diverse range of substances. Its characterization involves measuring concentration, identifying chemical species, and evaluating particle size. PM₁₀ and PM_{2.5} refer to particles smaller than 10 µm and 2.5 µm, with lifespans from days to weeks, traveling long distances via atmospheric currents. PM can be formed of microscopic solids or liquid droplets so small that they can be inhaled and go deep in the lungs and even ending up in the bloodstream (depending on the particles diameter).
- **Nitrogen Oxides (NO_x)** refer to NO, which is a gas generally emitted from combustion processes, and to NO₂, which is commonly formed in the atmosphere when NO reacts with O₂ or O₃. NO₂ is a reddish-brown gas with a pungent, suffocating odour at high concentrations. It is highly toxic, irritating the respiratory system and causing acute coughing,

⁴ European Environment Agency. (2020). *Air quality in Europe – 2020 report*. ISSN 1977-8449. EEA Report No 09/2020. DOI: 10.2800/786656

chest pain, convulsions, and circulatory failure at moderate levels. NO₂ can cause long-term lung damage and contributes to secondary particulate matter and ozone formation.

- **Sulphur Dioxide (SO_x)**, which is a common way to describe gaseous compounds based on sulphur and oxygen (mainly SO₂ and SO₃). It is a gas produced mainly from the combustion process of fossil fuels, which can cause acid rain and respiratory problems. This class of gas is colourless, nonflammable with a pungent, irritating odour. Highly soluble in water, it is classified as toxic. It strongly irritates the eyes and respiratory tract, and inhalation can cause pulmonary oedema. Prolonged exposure poses severe health risks, including the potential for fatal results.
- **Carbon Monoxide (CO)** is a highly toxic odourless, colourless, and tasteless gas from incomplete combustion of organic fuels such as coal, oil, wood, and gasoline. It binds strongly to the iron in haemoglobin, forming a stable complex that prevents oxygen transport. CO poisoning leads to reduced oxygen supply to the brain, unconsciousness, and potentially fatal asphyxiation.
- **Carbon Dioxide (CO₂)** is a greenhouse gas emitted by various combustion processes types, including in port areas, contributing to climate change.

Therefore, the performed air quality evaluation in areas of interest for each one of the selected maritime routes is based on the abovementioned air quality parameters since they are typical pollutants in port areas⁵.

In order to have an idea on the air pollution levels in the Adriatic Sea region, one can take a look at an interactive map developed by the European Environment Agency⁶ and verify the values for several types of relevant air quality parameters. Figure 1 and Figure 2 present examples for what concerns PM_{2.5} annual mean and NO₂ annual mean, respectively. In both cases the values refer to the year of 2023 and it is possible to observe the air quality levels not only for several points spread over both

⁵ Ducruet, C., Polo Martin, B., Sene, M. A., Lo Prete, M., Sun, L., Itoh, H., & Pigné, Y. (2024). Ports and their influence on local air pollution and public health: A global analysis. *Science of The Total Environment*, 915, 170099. <https://doi.org/10.1016/j.scitotenv.2024.170099>

⁶ <https://www.eea.europa.eu/en/analysis/maps-and-charts/air-quality-statistics-dashboards>

Italy – Croatia



TransH2

countries, but also for the regions of interest for this project, i.e., the regions of Venice, Ancona, and Split. Sections 3 to 5 present this aspect in more detail for each selected maritime route.

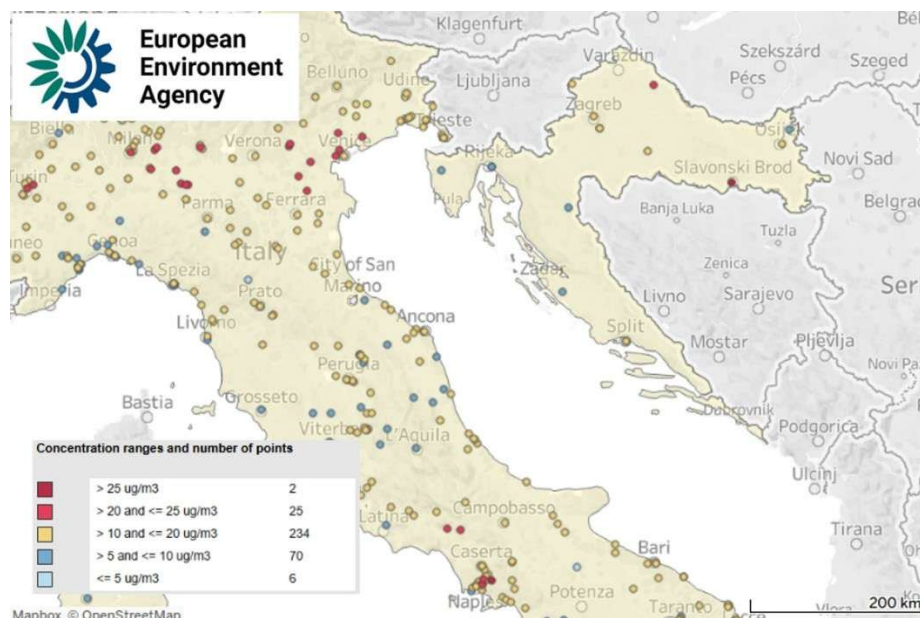


Figure 13. Annual mean for PM_{2.5} measurement through several stations spread over Italy and Croatia. Units are in $\mu\text{g}/\text{m}^3$.

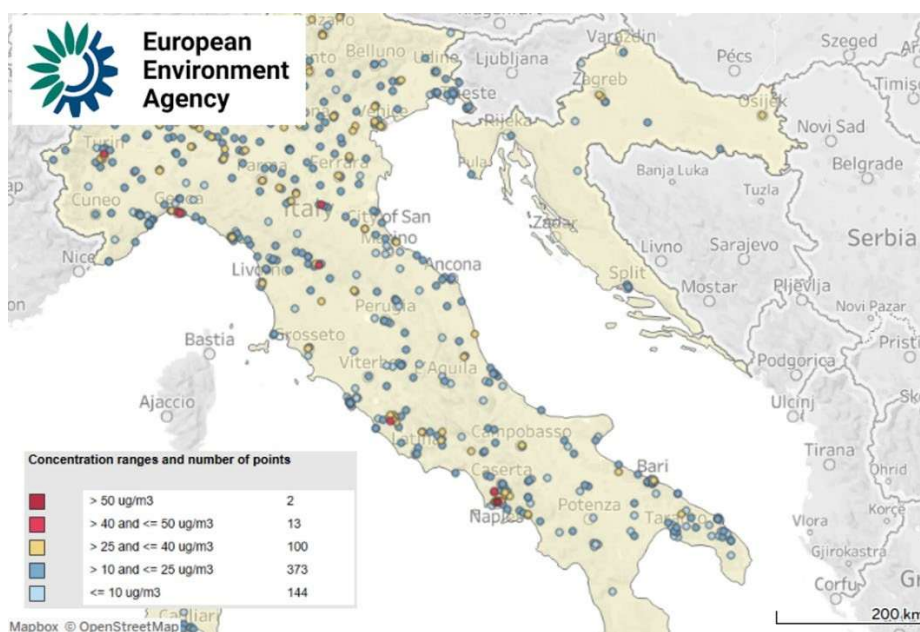


Figure 14. Annual mean for NO₂ measurement through several stations spread over Italy and Croatia. Units are in $\mu\text{g}/\text{m}^3$.

Italy – Croatia



TransH2

Natura 2000 sites

Natura 2000 is a network of protected areas across the European Union that was designated to preserve Europe's most valuable and threatened species and habitats. It is the largest coordinated network of conservation areas in the world⁷, forming the cornerstone of the EU's biodiversity policy. This network is based on the 1992 Habitats Directive and includes sites designated under the 1979 Birds Directive, meaning a given site may be protected under one or both directives. The network includes over 27,300 sites, covering 18% of EU land and 4% of marine areas, spanning more than 1.1 million square kilometres. Detailed information about these protected areas is available through an interactive map⁵ that displays all Natura 2000 sites across Europe.

The main goals of the Natura 2000 network are (i) to maintain or restore habitats and species, listed in the mentioned directives, to a favourable conservation status, and (ii) to ensure the sustainable use of resources while promoting the conservation of the local biodiversity. For this, the Natura 2000 network divides the sites into two main types: (i) Special Areas of Conservation (SACs), which are designated under the Habitats directive to protect natural habitats and species, and (ii) Special Protection Areas (SPAs), which instead are under the Birds directive to protect bird species and their habitats.

This network of sites does not exclude human activities, as long as they are sustainable and do not harm the site's ecological importance. Activities such as farming, forestry, and tourism are permitted if they are compatible with the network conservation goals. The importance of such measures includes the local biodiversity protection, the preservation of ecosystems that provide clean air, water, and other important resources, and the climate change mitigation.

The Natura 2000 interactive viewer map provides a detailed view of the exact location of each protected area under the Birds Directive and/or the Habitats Directive. This tool allows users to explore the spatial distribution and extent of these areas, highlighting the EU's efforts to preserve biodiversity. Figure 3 illustrates a screenshot of this map, focusing on the Adriatic Sea region, where numerous protected areas can be observed along the eastern Italian and Croatian coasts. On the Italian side, a significant concentration of Natura 2000 sites is located in the North Adriatic, particularly around the Delta del Po Park, the Venice Lagoon, and the Marano Lagoon. These areas are critical for their unique ecosystems and the rare species they support. On the Croatian coast, the map reveals an extensive network of protected areas spread across numerous islands, stretching from the northern to the southern coastline. This demonstrates Croatia's commitment to conserving its rich marine and terrestrial biodiversity. Additionally, Figure 3 allows the reader to see the exact location of the selected maritime routes, which gives a preliminary idea about the route situation for what concerns the Natura 2000 sites. The specific analysis for each selected route is developed through sections 3 to 5.

⁷ <https://www.eea.europa.eu/themes/biodiversity/natura-2000/the-natura-2000-protected-areas-network>

⁵ Natura 2000 Viewer. <https://natura2000.eea.europa.eu/expertviewer/>

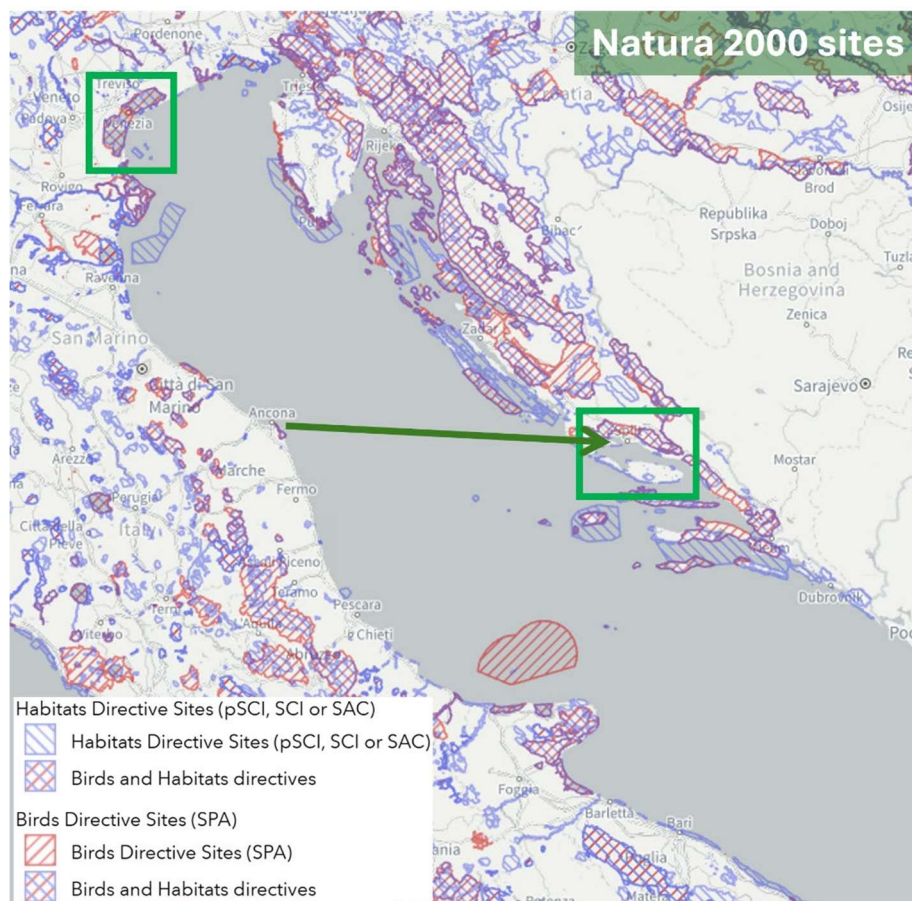


Figure 15. Natura 2000 network viewer: Adriatic Sea region plus the location of the selected maritime routes.

Navigational analysis

A navigational analysis of a maritime route generally involves several factors that influence the safety, efficiency, and feasibility of the maritime navigation along the pathway from point A to point B. In such analysis, the considered key aspects can include the route characteristics, environmental conditions, operational aspects, safety and risk factors, and regulatory/legal constraints.

The **route characteristics** are an essential aspect of a navigational analysis, as they define the physical and geographical parameters along the maritime route. This includes identifying the precise coordinates, distance, and layout of the route, as well as crucial waypoints, turning points, and recommended or mandatory navigational paths. Bathymetry plays a vital role to determine a safe passage, ensuring vessels avoid shallow waters and submerged hazards. The availability of navigational aids, such as lighthouses, buoys, and beacons, are analysed to support effective navigation. All these aspects are essential to ensure safe navigation and avoid human errors, which

were the cause of almost 60% of grounding and collision issues as for the end of the last decade⁸. The navigational risks can be further reduced by applying specific methodologies⁹ to find an optimal route planning that can, not only reduce risks, but also improve efficiency by shortening the route.

Environmental conditions are critical for navigational analysis, as they influence directly the safety and efficiency of maritime route operations. These conditions can be divided essentially into two main categories: meteorological and oceanographic aspect. Meteorological factors include existing weather patterns, such as winds (direction and velocity), storms, and seasonal variations, which can impact vessel handling, efficiency, and scheduling. Oceanographic aspects, including waves' height and direction, tides, and currents, are analysed to assess their effect on stability and fuel consumption since, depending on the intensity and direction, they can hamper navigability. For what concerns stability, for instance, a recent study¹⁰ has been published in which one of the aims was to investigate the influence of transverse wind and waves conditions on ship stability. One of the outcomes of the study was the definition of threshold categories (from low to high risk) for four environmental parameters (Table 9): ocean currents, waves' height, wind velocity and precipitation. According to the authors, transversal waves above 5 m and transversal wind velocity above 10 m/s constitute a medium to high risk for the ship stability.

Table 9. Classification table for key environmental parameters (Adapted from Guo, Z. et al. (2023)).

Environ. parameter	Risk classification				
	High	Higher	Medium	Lower	Low
Ocean current (m/s)	>2	1.5–2	1 ~1.5	0.5–1	<0.5
Waves (m)	>7	5~7	3~5	1 ~3	<1
Wind (m/s)	>14.4	10.8–14.4	7.2–10.8	3.6–7.2	<3.6
Precipitation (mm/h)	>16	12 ~16	8 ~12	4 ~8	>4

Operational aspects in navigational analysis focus on optimizing maritime route operation efficiency while ensuring safety and agreement to relevant regulations. These include evaluating fuel consumption to determine the most cost-effective route, minimizing operational costs. Crew

⁸ Jeevan, J., Ramamoorthy, K., Salleh, N.H.M. et al. Implication of e-navigation on maritime transportation efficiency. *WMU J Marit Affairs* **19**, 73–94 (2020). <https://doi.org/10.1007/s13437-020-00194-z>

⁹ Jang, D.-u.; Kim, J.-s. Development of Ship Route-Planning Algorithm Based on Rapidly-Exploring Random Tree (RRT*) Using Designated Space. *J. Mar. Sci. Eng.* **2022**, *10*, 1800. <https://doi.org/10.3390/jmse10121800>

¹⁰ Guo, Z., Hong, M., Zhang, Y., Shi, J., Qian, L., & Li, H. (2023). Research on safety evaluation and weather routing optimization of ship based on roll dynamics and improved A* algorithm. *International Journal of Naval Architecture and Ocean Engineering*, *16*, 100605. <https://doi.org/10.1016/j.ijnaoe.2024.100605>



workload is another critical factor. By ensuring a planned route, adequate rest periods and manageable operations are reached and hence safety standards are kept. Port shift times can be also evaluated with the aim to allow optimal berthing and departure schedules to reduce delays. Additionally, operational aspects consider weather routing, enabling real-time adjustments based on forecasts, and the availability of safe anchorages and emergency procedures to handle unexpected situations effectively during the voyage. The operation efficiency of a ship in a specific route can be also an object for optimization¹¹ with the aim of reducing the carbon intensity associated to the route.

Safety and risk factors are very important when it comes to navigational analysis. They focus on identifying and mitigating potential hazards along the maritime route. Key considerations include the risks of collisions and groundings, particularly in areas with high vessel traffic, narrow passages, or shallow

waters. Navigational hazards such as reefs, wrecks, and any type of underwater obstructions should be carefully evaluated. Security risks, though minimal in regions like the Adriatic Sea, are also assessed for vigilance. Emergency measures, including the availability of rescue stations, safe anchorages, and evacuation routes, should be mapped out. The scientific community has contributed¹² to the study of safety and risk management in maritime routes by establishing factors that affect maritime accident casualties and acknowledging patterns changes in maritime accidents.

Regulatory and legal constraints ensure navigational compliance with international, regional, and local maritime laws. The main law constraints include the IMO conventions, such as SOLAS¹¹ (International Convention for the Safety of Life at Sea) and COLREG¹³ (Convention on the International Regulations for Preventing Collisions at Sea), MARPOL¹⁴ (International Convention for the Prevention of Pollution from Ships), as well as specific national regulations governing territorial waters. The presence of SECA (Sulphur Emission Control Areas) and NECA (Nitrogen Emission Control Areas) constitutes environmental regulations and require vessels to minimize air pollutants by using low-sulphur fuels or implementing exhaust treatment systems, which can influence route planning and fuel costs. Additional constraints may include avoiding ecologically sensitive zones, such as the Natura 2000 sites.

¹¹ Yuan, Q., Wang, S., & Peng, J. (2023). Operational efficiency optimization method for ship fleet to comply with the carbon intensity indicator (CII) regulation. *Ocean Engineering*, 286, 115487. <https://doi.org/10.1016/j.oceaneng.2023.115487>

¹² Zhou, K., Xing, W., Wang, J., Li, H., & Yang, Z. (2024). A data-driven risk model for maritime casualty analysis: A global perspective. *Reliability Engineering & System Safety*, 244, 109925. <https://doi.org/10.1016/j.res.2023.109925> ¹¹ [https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-\(SOLAS\),-1974.aspx](https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx)

¹³ <https://www.imo.org/en/About/Conventions/Pages/COLREG.aspx>

¹⁴ [https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-\(MARPOL\).aspx](https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx)



Transport models

The utilization of hydrogen as a fuel for maritime vessels represents a significant step forward in the maritime industry's transition toward sustainable operations. According to the International Maritime Organization¹⁵, the share of global Greenhouse Gas (GHG) emissions in the maritime transportation sector has increased from 2.76% (977 million tonnes of CO₂ equivalent) in 2012 to 2.89% (1,076 million tonnes of CO₂ equivalent) in 2018. Therefore, there is a substantial importance to investigate solutions that can support the mitigation of emissions in the maritime sector. As the solution presented by the TransH2 project is the transition from traditional Diesel-powered vessels to hydrogen-powered vessels, it is crucial to evaluate the potential environmental benefits of such a transition by comparing fuel consumption and corresponding emissions within both scenarios, i.e., before and after the transition. In this project the scenarios are applied for the ferry boats currently operating on the three selected maritime routes.

The analysis of fuel consumption and the resulting emissions (in this case, NO_x, CO₂, and SO_x) from ferries operating on the selected maritime routes is conducted by using a model developed by the University of Trieste. The model enables the assessment of the ferry emissions by integrating key operational parameters such as fuel type, engine specifications, and route characteristics. Furthermore, it allows the estimation of the required hydrogen amount that enables these ferry boats to navigate in fuel-cell powered mode, thereby reducing their reliance on conventional fossil fuels.

Therefore, the analysis provides valuable insights into the potential reductions in GHG emissions achievable through the adoption of hydrogen technology in maritime transport, highlighting its role in promoting cleaner and more sustainable operations. In the sections 3.3, 4.3, and 5.3 (dedicated to each selected maritime route), the reader can find the technical data concerning the involved technologies, as well as the input data and results obtained from the analysis of fuel consumption and the resulting emissions.

Objectives

The purpose of this deliverable is to provide a comprehensive analysis of the three selected maritime routes, as outlined in Deliverable D.2.1.2. This detailed analysis encompasses three key components: (i) an environmental analysis encompassing an air quality assessment in the regions surrounding the seaports associated with each route, the consideration of the Natura 2000 sites locations, and a CO₂ emissions avoidance calculation, (ii) a navigational evaluation that integrates meteorological and oceanographic considerations, and (iii) the presentation of transportation models designed to predict hydrogen consumption. The prediction is based on critical factors derived from both the characteristics of the maritime routes and the specifications of the vessels operating on them.

¹⁵ <https://www.imo.org/en/ourwork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx>

Presentation of the 3 selected maritime routes

As concluded in the deliverable D.2.1.2, the online workshop and the following survey allowed the TransH2 project partners to identify, with the contribution of the most active interested parties, the three use-cases that will be subject to further investigation for the transition towards H2 technology. The three use-cases are: Tronchetto-Lido (Figure 4), Split-Supetar (Figure 5), and Ancona-Split (Figure 6).

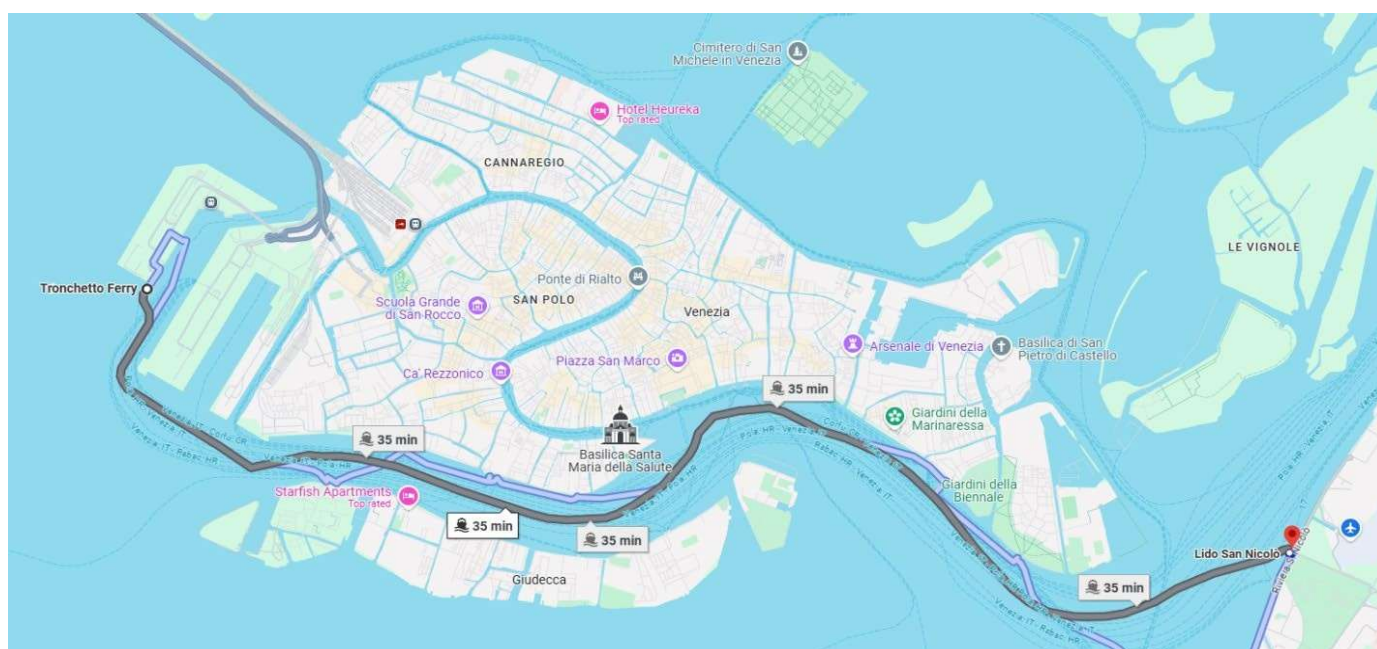


Figure 16. Tronchetto-Lido maritime route. Use-case for regional maritime routes in Italy.

Italy – Croatia

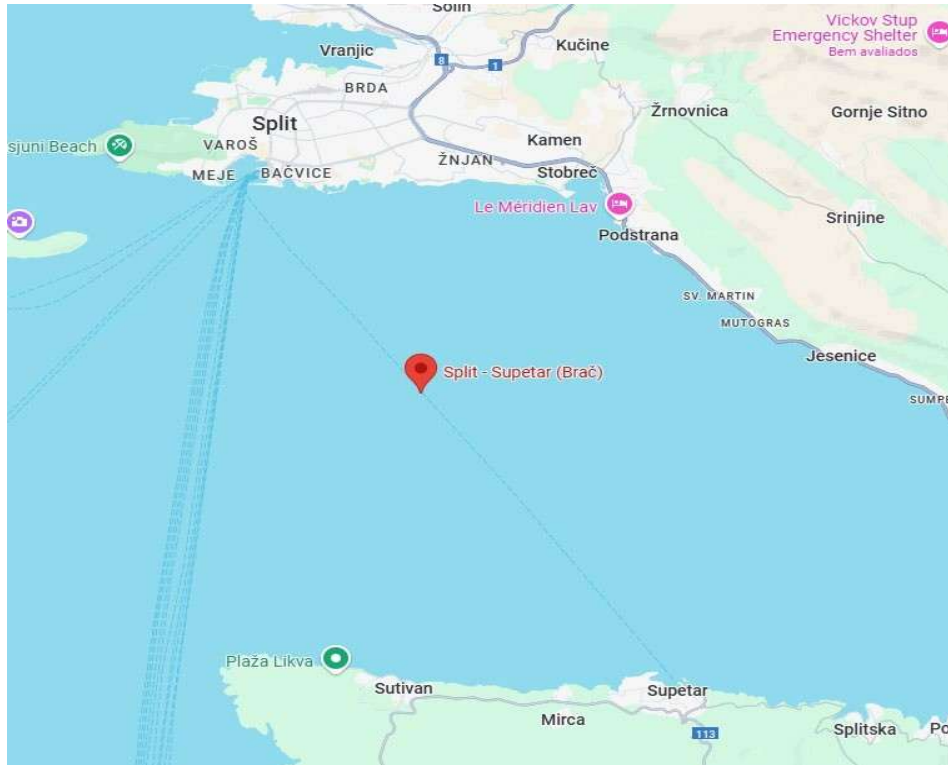


Figure 17. Split-Supetar maritime route. Use-case for regional maritime route in Croatia.

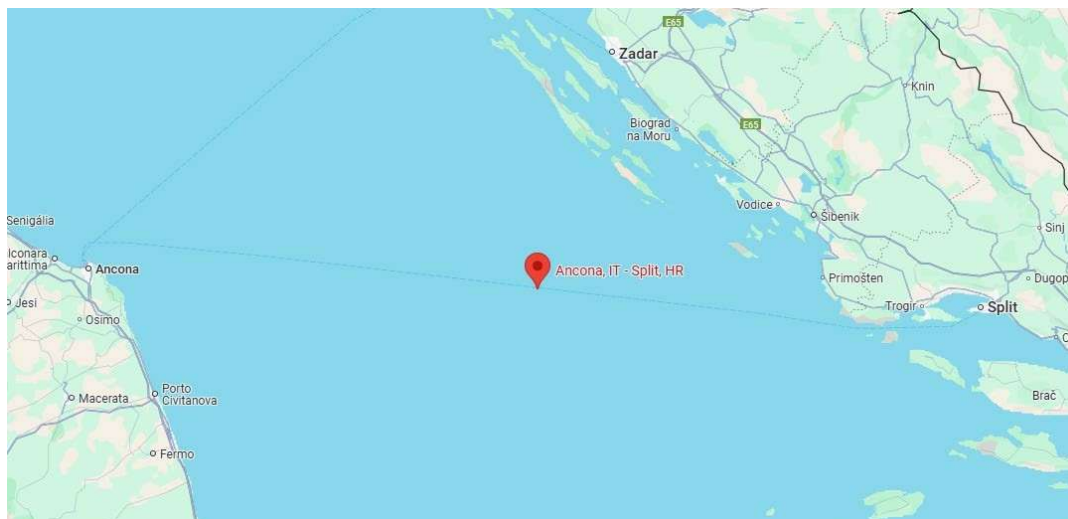


Figure 18. Ancona-Split maritime route. Use-case for international maritime route Italy-Croatia.

Italian regional route – Tronchetto-Lido

Tronchetto, also known as the "Isola Nuova", is an artificial island in Venice (Figure 7), built on the 1960s, that serves as a major hub for parking and transportation. It features one of the Venice's largest car parks, providing a convenient place for visitors to leave their vehicles before entering the car-free historic centre. The island is connected to Piazzale Roma and the port terminal via the "People Mover" (a light-rail system), and offers ferry services for vehicles and water buses to various parts of Venice. Tronchetto also serves as a logistics hub, facilitating the transfer of goods into the city via smaller boats.

Lido di Venezia instead, commonly known as the Lido, is a natural narrow barrier island in the Lagoon of Venice that separates Venice from the Adriatic Sea (Figure 19). Renowned for its sandy beaches, it offers a peaceful refuge from the energetic historic centre of Venice. The Lido is also famous for hosting the prestigious Venice Film Festival, held annually at the Palazzo del Cinema. Accessible by ferry, the Lido allows cars, unlike Venice itself.



Figure 19. Tronchetto artificial island, Venice (Source: Google Earth).



Figure 20. Lido di Venezia (Source: Google Earth).

The maritime route between Tronchetto and Lido di Venezia is performed by using ferry boats such as the Metamauco (Figure 20) passenger/Ro-Ro cargo ship, operated by ACTV, which is a public company responsible for the public transportation in the Venice municipality.



Figure 21. Metamauco RO-RO vessel operated by ACTV.

Environmental analysis

As explained in the section 1.1, the environmental evaluation is performed in terms of air quality assessment and considerations regarding the Natura 2000 sites.

Air quality

The ARPAV (*Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto* or Veneto Regional Agency for Environmental Prevention and Protection) air quality monitoring network in the Municipality of Venice has been operational since 1999. That year, fixed monitoring stations, previously managed by the Municipal and Provincial Administrations, were transferred to ARPAV in

compliance with regional regulations. ARPAV is the regional agency responsible for environmental protection and prevention in Veneto, supervising activities such as air quality monitoring, environmental data collection, and pollution management. In 2023, the regional network in the Province of Venice consisted of six fixed monitoring stations and one mobile laboratory. The data gathered in this section of the TransH2 project, deliverable D.2.1.3, is based on the 2023 air quality report¹⁶ issued by the Venice municipality and is focused on two of the six monitoring stations located in the region of Venice, i.e., Rio Novo and Sacca Fisola (Figure 22), which are very close to the region of the Tronchetto-Lido maritime route.

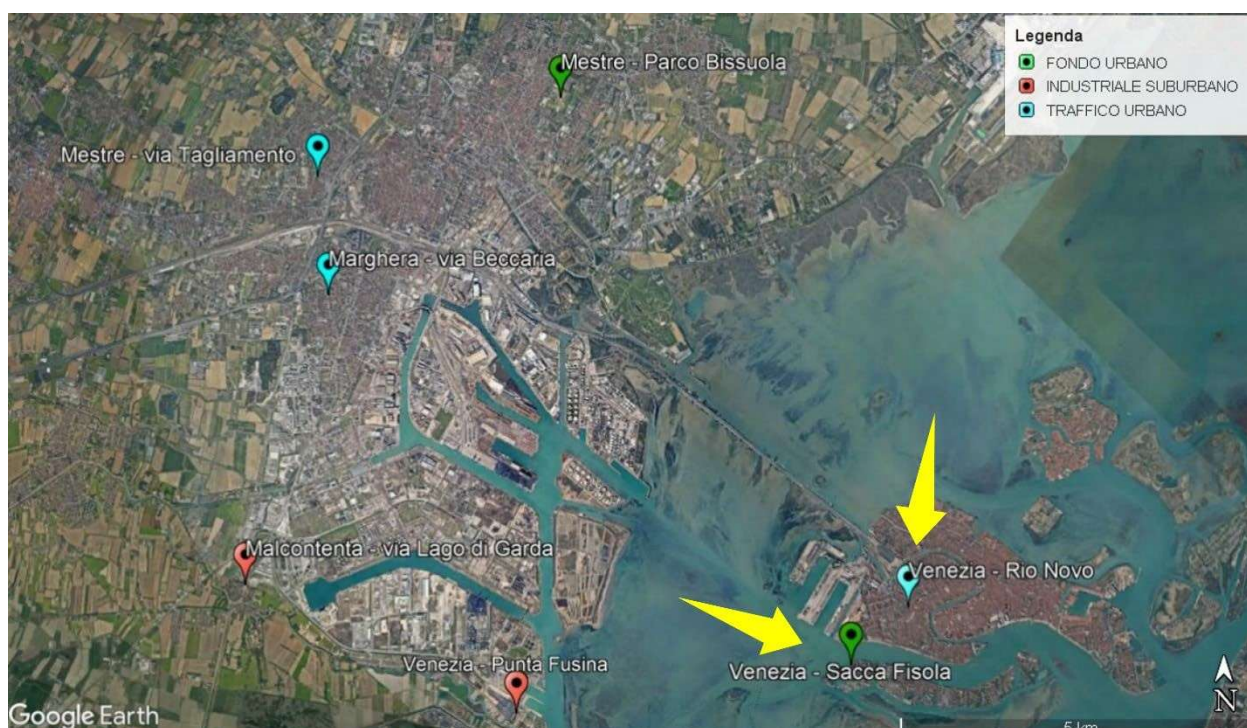


Figure 22. Map of the Venice municipal territory with the location of fixed monitoring stations as at December 31st, 2023.
Adapted from the 2023 air quality report from the Venice municipality.

Each monitoring station has different types of instrumental equipment capable of measuring different types of air quality parameters (Table 2). The Sacca Fisola monitoring station is able to measure SO₂, NO_x, O₃ and PM₁₀, whereas the Rio Novo monitoring station is able to measure NO_x, CO, O₃, PM_{2.5}, and PM₁₀. Therefore, based on what was explained in section 1.1.1, the air quality analysis for the Tronchetto-Lido maritime route is based on the parameters SO₂, NO₂, CO, and PM.

Table 10. Air quality measured parameters for each analysed monitoring station in the Venice region.

Stations	SO ₂	NO _x	CO	O ₃	PM _{2.5}	PM ₁₀
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¹⁶ <https://www.comune.venezia.it/it/content/stato-qualit-dellaria>

Italy – Croatia



Sacca Fisola	✓	✓	-	✓	-	✓
Rio Novo	-	✓	✓	✓	✓	✓

Sulphur dioxide (SO₂)

Sulphur dioxide is primarily produced during the combustion of solid and liquid fuels due to the presence of sulphur, either as an impurity or a molecular component of the fuel. At the region of Venice, the main sources of SO₂ emissions include industrial combustion, energy production and fuel processing, nonindustrial combustion, and manufacturing processes. SO₂ concentrations typically peak during the central hours of the day. Its emission levels and environmental impact are closely monitored due to its toxic nature and its contribution to air pollution and respiratory health issues.

The SO₂ concentrations in the Municipality of Venice has been below the thresholds established by the local Legislative Decree 155/10 (reference standard in the field of air quality in the region¹⁷). Key indicators include a 500 µg/m³ alarm threshold, an hourly limit of 350 µg/m³ (not to be exceeded more than 24 times annually), and a daily limit of 125 µg/m³ (not to be exceeded more than three times annually). From 2003 to 2023, SO₂ levels consistently complied with these standards, except for two occasions in 2005 at a specific location in the Municipality of Venice (although relatively far from the region of Tronchetto-Lido maritime route), where the hourly limit was briefly exceeded.

The long-term trend shows stabilization of average ambient concentrations below 10 µg/m³, confirming that SO₂ is no longer a critical primary pollutant in the region. This improvement is largely attributed to the transition from fuels like diesel and oil to cleaner alternatives, such as natural gas, as well as the reduction of sulphur content in fuels. These measures have significantly lowered SO₂ emissions, maintaining levels well below regulatory limits and ensuring better air quality in Venice.

Nitrogen dioxide (NO₂)

The primary anthropogenic sources of NO₂ in Venice include road transport, industrial activities, residential combustion, and other transport sectors like seaport and airport operations. Ambient NO₂

concentrations fluctuate daily, influenced by traffic patterns, atmospheric dispersion, and photochemical reactions. The Legislative Decree 155/10 defines two key thresholds for NO₂: an hourly limit of 200 µg/m³ (exceedance allowed 18 times annually) and an annual limit of 40 µg/m³ for human health protection.

¹⁷ <https://www.arpa.veneto.it/temi-ambientali/aria/cosa-dice-la-normativa>

Italy – Croatia

TransH2

From 2003 to 2023, occasional exceedances of the hourly limit were recorded, but not regarding the stations of Rio Novo or Sacca Fisola, near the Tronchetto-Lido maritime route. For instance, in 2016, the station at Via Beccaria in Marghera reached the maximum permissible 18 exceedances. However, from 2020 to 2023, no hourly limit exceedances were reported, marking a significant improvement.

Annual averages also demonstrated a positive trend (Figure 11). While some urban and water traffic monitoring stations, such as Via Tagliamento and Rio Novo, recorded annual averages above the 40 $\mu\text{g}/\text{m}^3$ limit between 2008 and 2019, concentrations have generally declined since 2020. Factors such as decreased traffic and improved fuel quality contributed to this improvement.

By 2023, most monitoring stations reported the lower annual averages in the historical record, except for Rio Novo station, which reported an annual average of 36 $\mu\text{g}/\text{m}^3$ while all the other stations reported annual averages up to 27 $\mu\text{g}/\text{m}^3$.

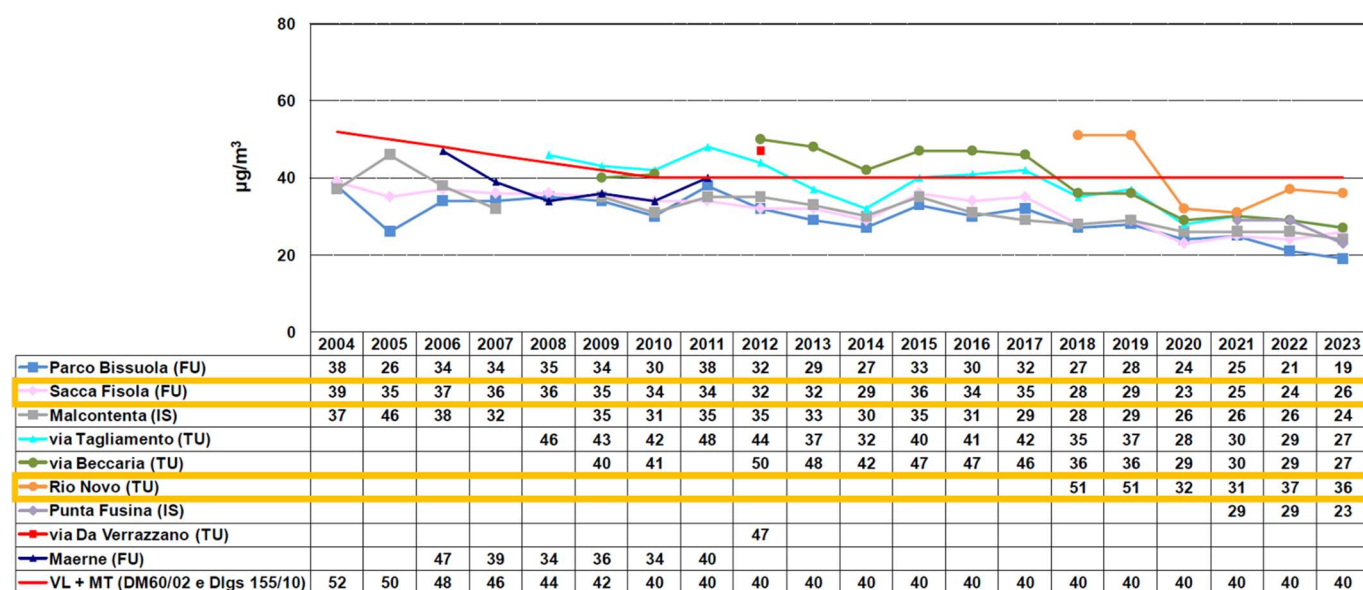


Figure 23. NO₂ annual average measurement for different monitoring stations in the Municipality of Venice (air quality report, 2023).

Carbon monoxide (CO)

In the Venice region, the main anthropogenic sources of CO emissions are non-industrial combustion, followed by road transport. Ambient air concentrations throughout the day are primarily influenced by traffic flow. According to the previously mentioned Legislative Decree 155/10, the health protection limit for CO is set at a maximum daily 8-hour moving average of 10 mg/m^3 . From 2003 to 2023, CO levels measured in the Municipality of Venice consistently remained within this limit. Historical data shows a trend toward stabilization, with average concentrations falling below 1 mg/m^3 in urban areas. Currently, CO is not considered a pollutant of concern.

Particulate matter (PM2.5 and PM10)

The analysis of PM concentrations highlights significant trends and seasonal variations influenced by atmospheric conditions and emission sources. PM levels are typically higher in winter, driven by poor pollutant dispersion and increased emissions from heating and other sources. The regulatory limits for PM 10 are 50 $\mu\text{g}/\text{m}^3$ (daily limit - not to be exceeded more than 35 times annually) and 40 $\mu\text{g}/\text{m}^3$ (annual average). For PM2.5, the annual average limit is 25 $\mu\text{g}/\text{m}^3$.

Annual average concentrations of PM10 have shown a long-term decreasing trend across monitoring stations (Figure 12). At the Rio Novo and Sacca Fisola stations, close to the Tronchetto-Lido maritime route, the main observations include:

- Rio Novo Station: PM10 monitoring began in 2018. Since then, the annual average concentrations have remained below the limit of 40 $\mu\text{g}/\text{m}^3$, following a marked decline in 2021 when the station recorded its lowest historical values (probably due to the influence of the COVID-19 pandemic). The trend stabilized from 2022 to 2023, with averages consistently below the legal threshold.
- Sacca Fisola Station: The data reflects similar improvements, particularly after 2008, when concentrations consistently fell below the annual limit. The station recorded a minimum historical average in 2014 (28 $\mu\text{g}/\text{m}^3$), with subsequent measurements fluctuating between 29 $\mu\text{g}/\text{m}^3$ and 36 $\mu\text{g}/\text{m}^3$.

During the monitored period, neither station reported more than the allowed 35 daily exceedances of 50 $\mu\text{g}/\text{m}^3$ per year, reflecting progress in controlling PM10 pollution.

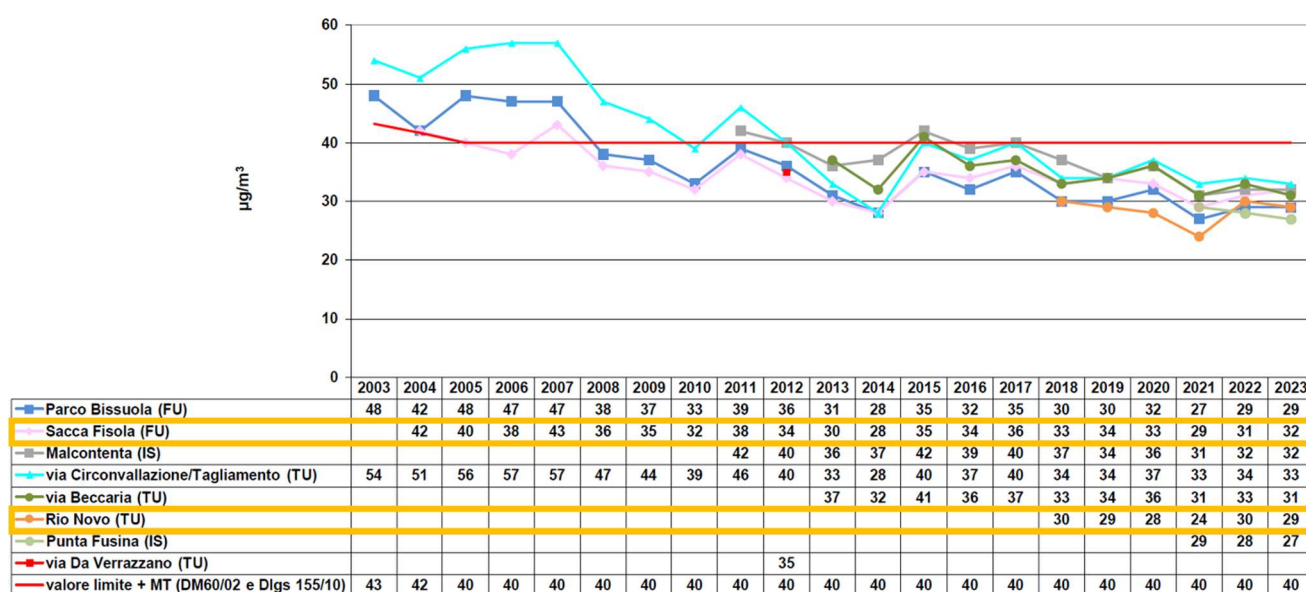


Figure142. PM10 annual average measurement for different monitoring stations in the Municipality of Venice (air quality report, 2023).

Italy – Croatia

TransH2

PM2.5 trends align closely with those of PM10, with overall concentrations decreasing over time (Figure 13). At Rio Novo station, where monitoring began in 2019, concentrations have remained below the annual limit of 25 $\mu\text{g}/\text{m}^3$. While 2020 saw a slight increase, subsequent years showed stabilization below the threshold. Sacca Fisola station have not measured PM2.5 concentrations.

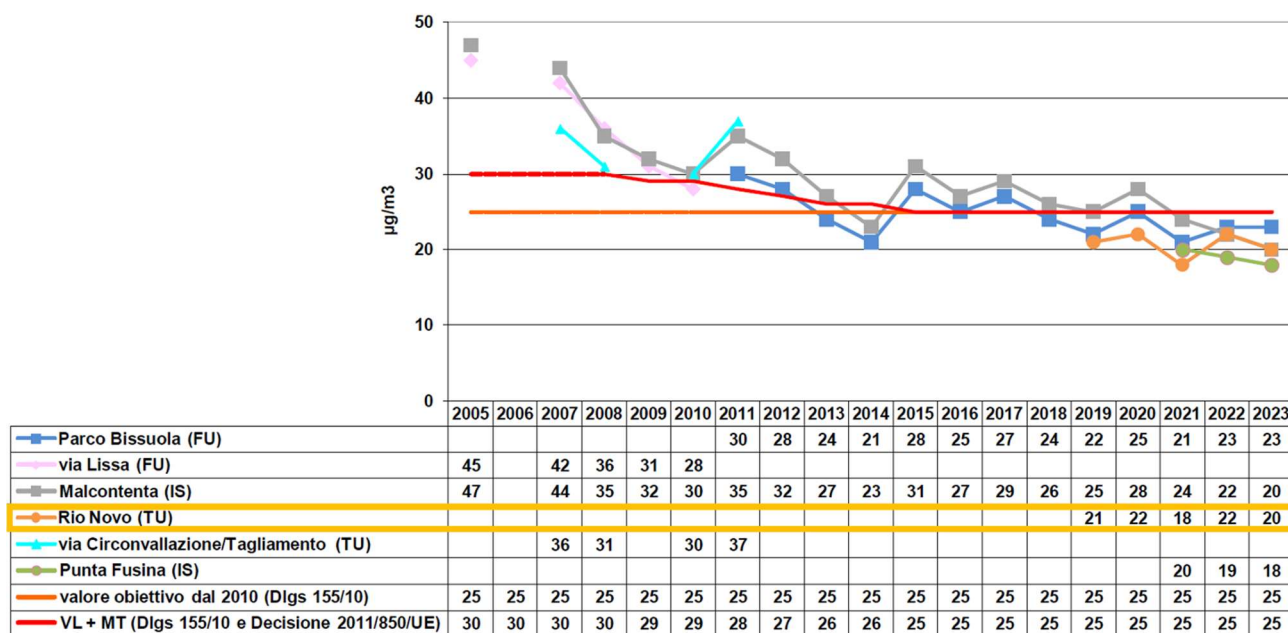


Figure 25. PM2.5 annual average measurement for different monitoring stations in the Municipality of Venice (air quality report, 2023).

Natura 2000 sites

Almost the entire Venice Lagoon is designated under one or both types of directives for Natura 2000 sites. Figure 14 illustrates the full extent of the lagoon, highlighting its key Natura 2000 areas. In the northern part lies the *Laguna Superiore di Venezia* (site code: IT3250031, covering 203.4 km²). The central section features the *Laguna di Venezia* (site code: IT3250046, covering 84.6 km²), while the southern region includes the *Laguna Medio-Inferiore di Venezia* (site code: IT3250030, covering 263.6 km²).

The Tronchetto-Lido maritime route is located in the central section of the lagoon and crosses the Natura

2000 site *Laguna di Venezia*, mainly in the part of the route between the Venice and Lido islands (Figure 15).

According to the Natura 2000 platform, the Venice Lagoon is characterized by a complex system of water bodies, river mouths, salt marshes, channels, and wetlands, with large areas primarily used for fish and mollusc farming. Its natural landscape features open water spaces with submerged

Italy – Croatia



TransH2

macrophyte vegetation and extensive flat islets (barene) that host halophytic plant communities, including some endemic to the northern Adriatic region.

This region holds exceptional importance for overwintering and migratory wetland birds, particularly herons, ducks, and shorebirds. It is also an important nesting site for various bird species, including terns and Charadriiformes. The lagoon is home to endemic plant and animal communities, as well as rare and threatened species of regional and national significance.

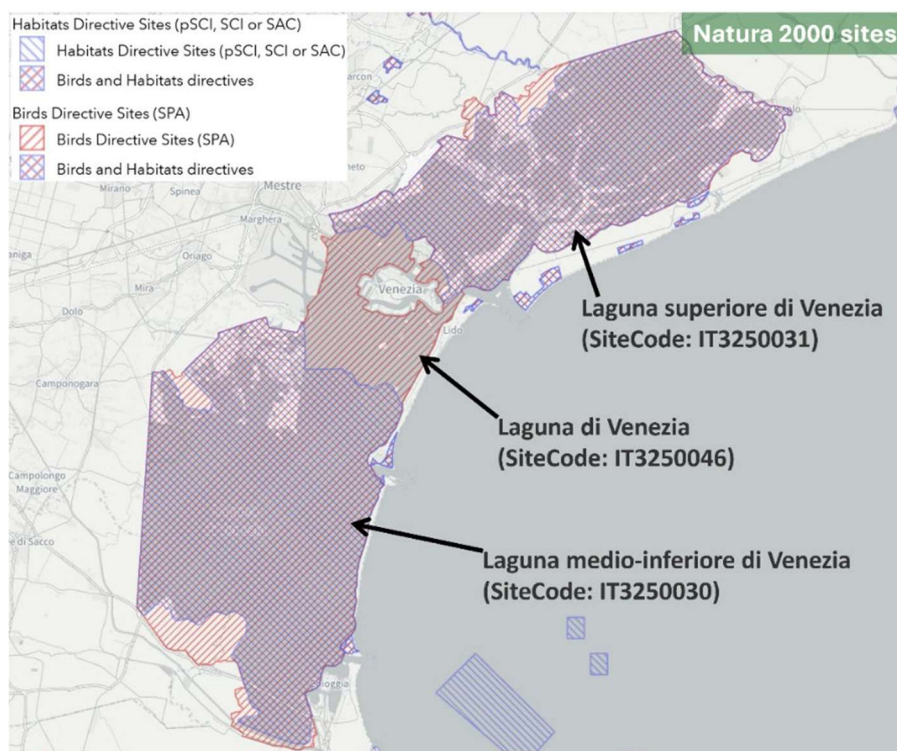


Figure 26. Natura 2000 sites in the Venice Lagoon.

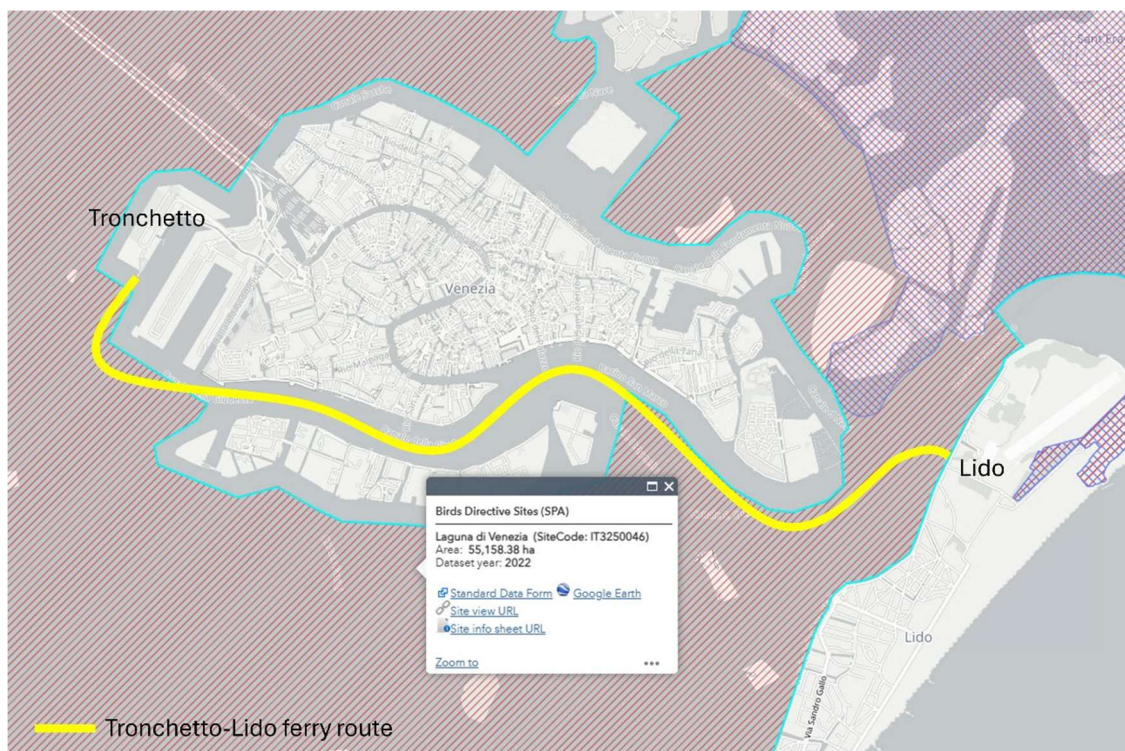


Figure 27. Relation between the Tronchetto-Lido maritime route and the local Natura 2000 site.

Navigational analysis

The navigational analysis for the Tronchetto-Lido maritime route is focused on two main aspects: the characteristics of the route (coordinates, length, and bathymetry) and the environment conditions (wind direction and velocity as well as waves direction and height).

Characteristics of the Tronchetto-Lido maritime route

The coordinates of the two involved maritime terminals are as follows:

- Tronchetto terminal is located at the latitude 45.438135° N and the longitude 12.303987° E.
- Lido terminal, specifically the Lido San Nicolò station, is situated at the latitude 45.425655° N and longitude 12.378255° E.

The length of the route is approximately 7 km (3.7 Nautic Miles), always considering the Lido San Nicolò station. The ferry service operates between these two points, typically taking between 35 to 40 minutes to complete one-way journey.

The bathymetry of the Venice Lagoon area is characterized by relatively shallow waters. In fact, the Lido entrance and several other pathways in the lagoon (including the one between Tronchetto and Lido San Nicolò) have been dredged to a greater depth to accommodate big ships, while the surrounding lagoon areas are shallower, as observed in Figure 16. It is possible to see that the

average depth in the pathway between Tronchetto and Lido San Nicolò is somewhere between 10 to 15 meters.



Figure 28. Bathymetry of the Venice Lagoon region¹⁸.

Figure 17 provides a more detailed bathymetry view for the area near the Tronchetto terminal. As observed the depth in the zone varies between 5 and 15 meters and is characterized by some particular marks, namely Dredging marks, Keel marks, and Propeller scour holes.

¹⁸ Madricardo, F., Foglini, F., Campiani, E. et al. Assessing the human footprint on the sea-floor of coastal systems: the case of the Venice Lagoon, Italy. Sci Rep 9, 6615 (2019). <https://doi.org/10.1038/s41598-019-43027-7>

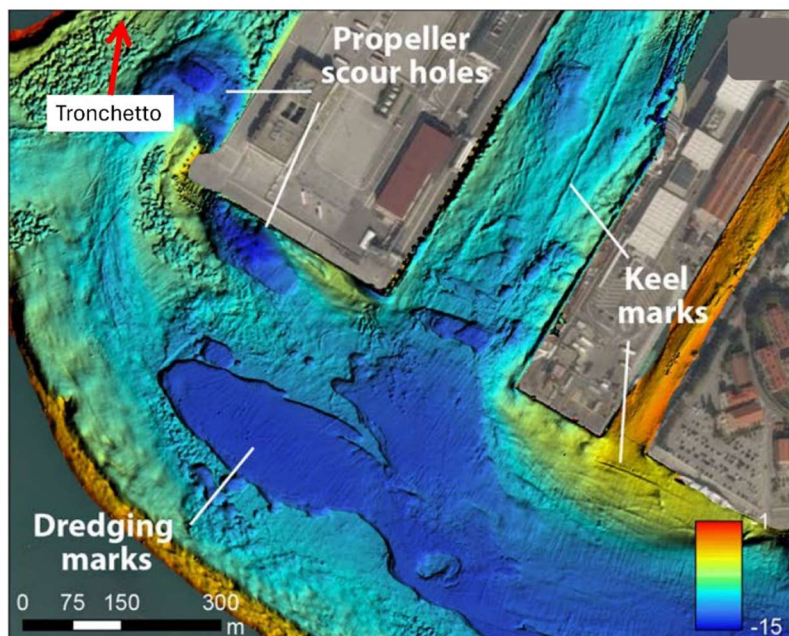


Figure 29. Detailed bathymetry near Tronchetto terminal¹⁹.

Meteorological and oceanographic conditions

As stated in the beginning of section 3.2, the meteorological analysis of this report is focused on the wind conditions of the region under analysis, while the oceanographic analysis is focused on the wave conditions of the region under analysis. All the data presented in this section has been collected in the ISPRA website²⁰.

Wind speed and direction analysis

Figure 30 presents the annual average wind speed and direction for the region of Venice in the years of 2013, 2016, 2019, and 2023. As observed, the wind direction pattern has not varied significantly in the past 10 years. For the four selected years, there is a predominance of wind coming from the Northeast (NE) and North-Northeast (NNE) directions, with a speed range varying from about 1 to 14 m/s.

¹⁹ Madricardo, F., Foglini, F., Campiani, E. et al. Assessing the human footprint on the sea-floor of coastal systems: the case of the Venice Lagoon, Italy. *Sci Rep* 9, 6615 (2019). <https://doi.org/10.1038/s41598-019-43027-7>

²⁰ ISPRA – *Istituto Superiore per la Protezione e la Ricerca Ambientale* or Superior Institute for Environmental Protection and Research (<https://www.mareografico.it/en/stations-comparison.html>)

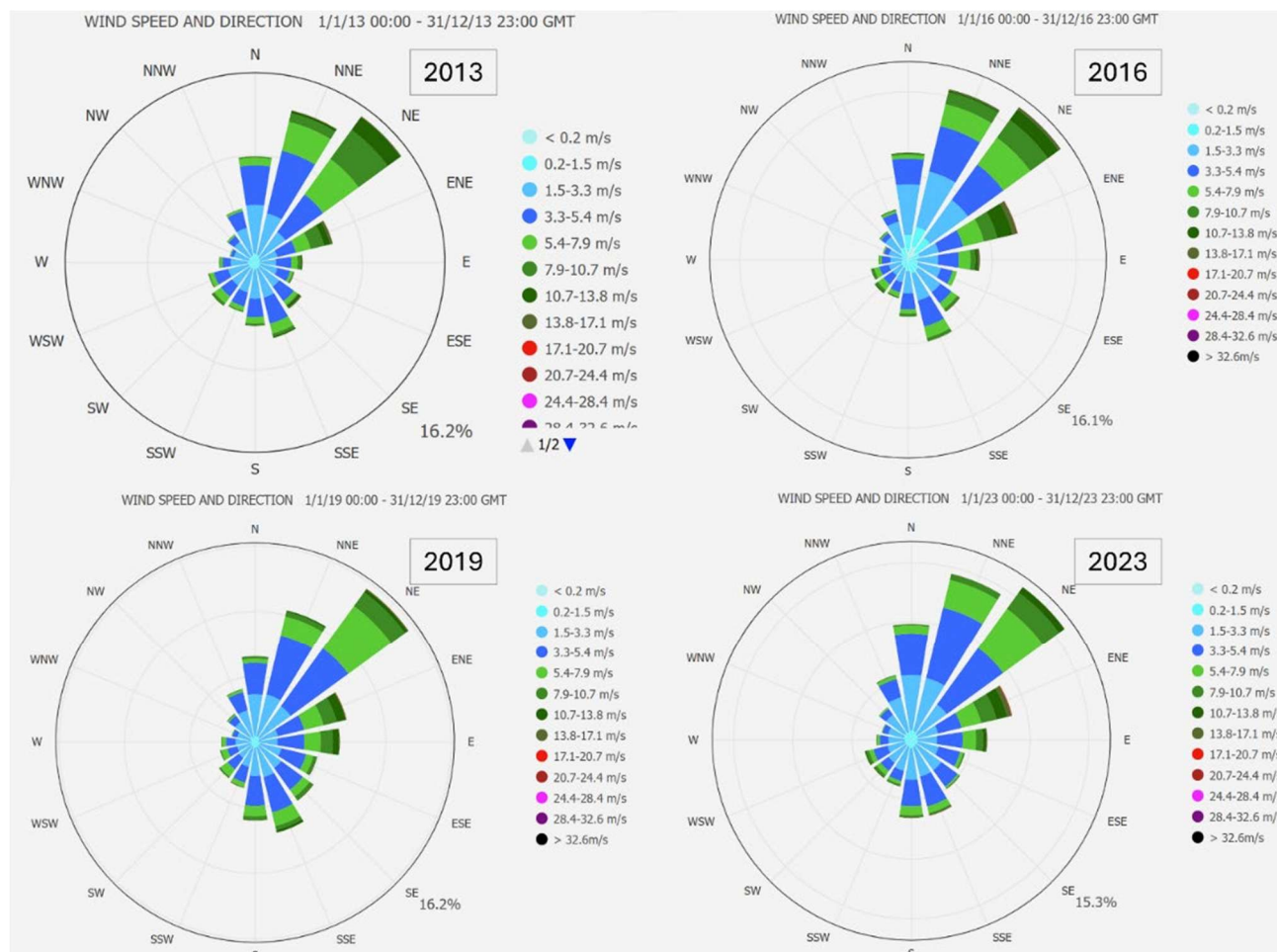


Figure 30. Annual average wind speed and direction in the Venice region, for the years 2013, 2016, 2019, and 2023.

In order to have an idea about the wind behaviour within a single year, Figure 31 provides the average wind speed and direction for the Winter, Spring, Summer, and Autumn of 2023. As observed, in fact there is a predominance of wind from the NE direction during the Winter, Spring, and Summer. However, during the Summer there is a secondary predominance of wind from the South-Southeast (SSE) direction. The wind from NE direction is due to the so called Bora Wind (a cold, dry, and gusty wind from the northeast), while the wind coming from the Southeast (SE) direction is attributed to the so called Scirocco Wind (a warm, humid wind from the SE, often bringing rain and higher sea levels).

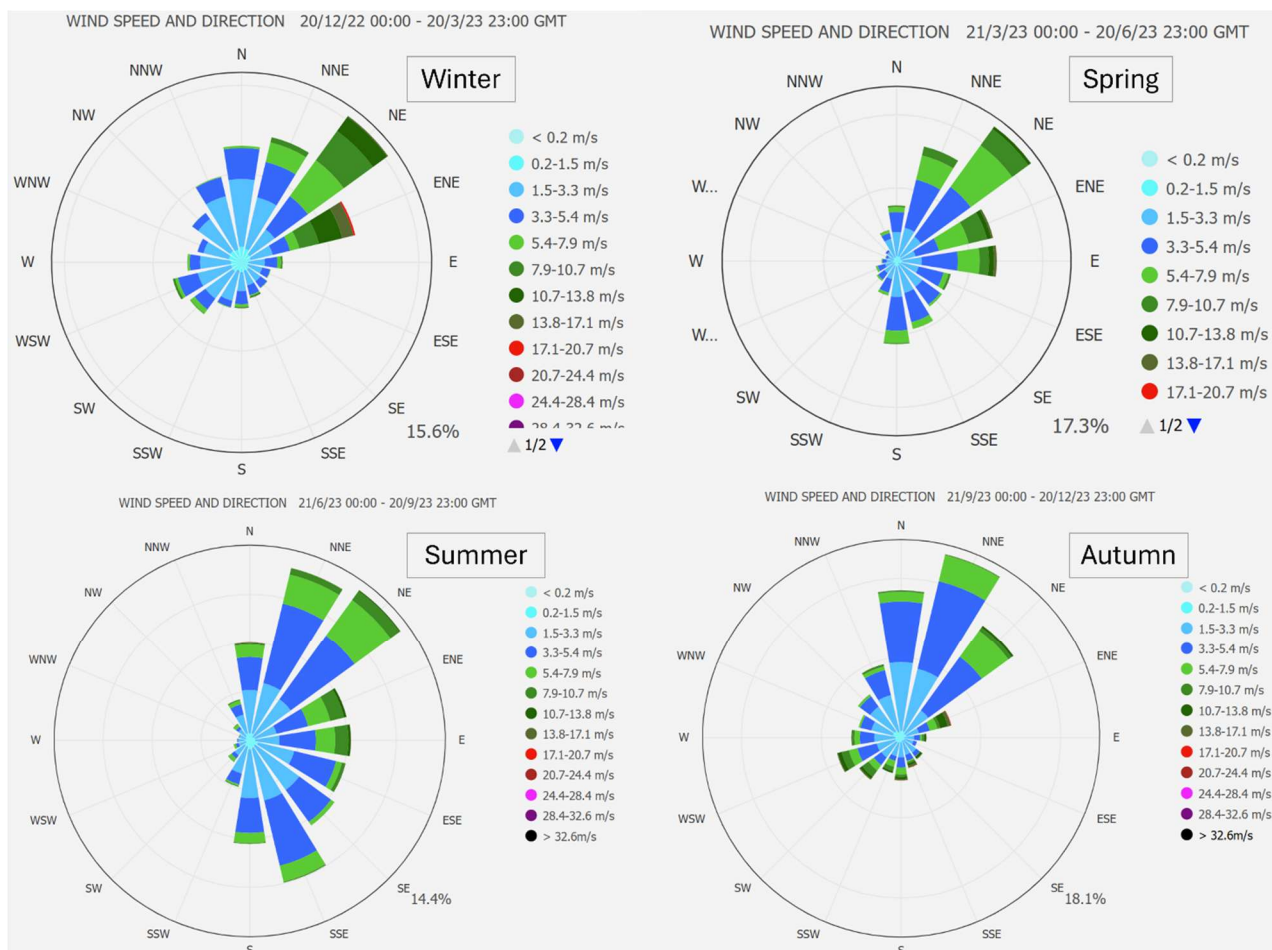


Figure 31. Average wind speed and direction in the Venice region, for the Winter, Spring, Summer, and Autumn of 2023.

Wave height and direction analysis

Figure 20 presents the average wave height and direction, in the Venice region, for the Winter, Spring, Summer, and Autumn of 2022. As observed, in terms of direction, there is a predominance of waves from Southeast (SE) during the Spring, Summer, and Autumn. The height of these waves ranges from approximately 0.5 to 2 meters, with a major occurrence of waves with heights up to 1.5 meters. In the Winter, however, there is a dominance of waves coming from the East-Northeast (ENE) direction, with heights within the range between 1 to 4 meters.

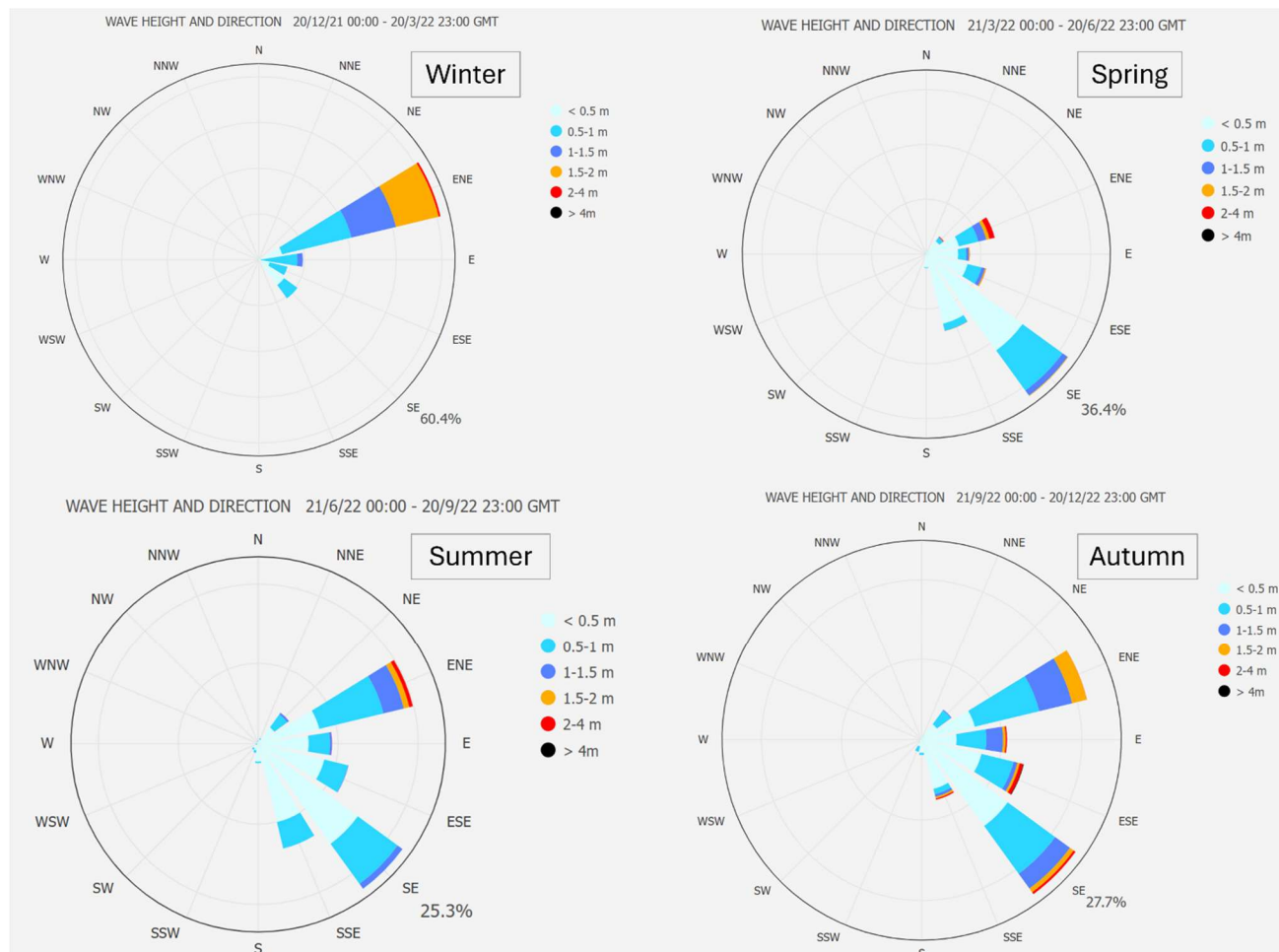


Figure 32. Average wave height and direction in the Venice region, for the Winter, Spring, Summer, and Autumn of 2022.

Transportation analysis

As outlined in the section 1.3, a model for evaluating ferry boat fuel consumption and emissions, developed by the University of Trieste, has been used to assess the potential reduction in greenhouse gas (GHG) emissions. Additionally, the model has been employed to estimate the required hydrogen amount either to retrofit existing vessels or to deploy new hydrogen-powered ferries along this route.

Table 11 introduces the main characteristics of the ferry boat presented in Figure 32, while Table 12 provides the characteristics of the Tronchetto-Lido maritime route.

Table 11: Characteristics of the Metamauco ferry boat (Figure 9).

Main engine (MW)	Max speed (kn)	Length Overall (m)	Engine Type	Beam (m)	Draught (m)	Depth (m)	Deadweight (t)
1.27	11	57.8	2 X CAT 3508 TA	13.1	2.6	3.02	500

Table 12: Characteristics of the Tronchetto-Lido maritime route.

Frequency (times/week)	Distance (NM)	Travel time (h)	Service speed (knots)
168	4.5	0.58	6

Starting from the ferry boat and route characteristic, the first step is to evaluate the engine required power at the route service speed. By considering a maximum ferry speed of 11 kn at 1.27 MW, it is possible to estimate a required power of 206 kWe at 6 kn of cruise speed.

To evaluate the ferry fuel consumption at the considered engine load, the data of the Caterpillar 3508TA²¹ marine diesel engine has been considered and, by assuming a Lower Heating Value (LHV) of 0.0119 kWh/g for marine diesel, the engine efficiency has been determined (Table 13).

Table 13: CAT 3508TA engine specifications from datasheet.

Engine load %	Power kW	Fuel consumption g/kWh	Efficiency %
50	400	231	36.5
75	600	220	38.3
100	800	218	38.8

Starting from the data in Table 11, the polynomial regression equation has been obtained and then used to estimate the engine efficiency by considering variable load. The coefficient used in the polynomial equation to calculate the engine efficiency is equal to the ratio of the required power 206 kW, over the installed power 1.27 MW (power ratio equal to 16).

²¹ https://www.cat.com/it_IT/products/new/power-systems/industrial/industrial-diesel-engines/18377766.html

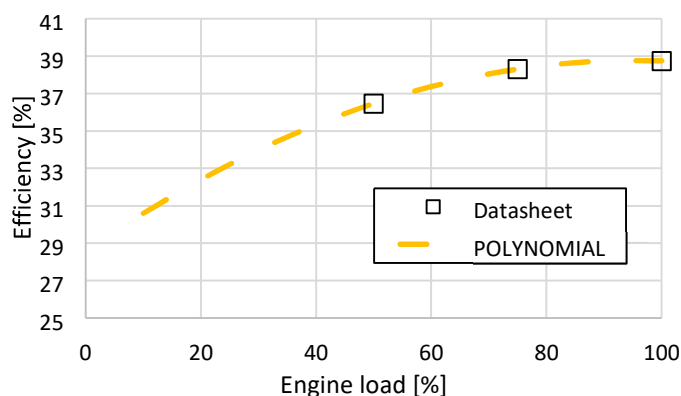


Figure 33. Determination of engine efficiency based on the polynomial regression line.

From the determined polynomial equation it is possible to estimate the engine efficiency and then calculate the fuel consumption for one trip (Table 14).

Table 14: Main results of the model based on one trip for the ferry boat Metamauco.

Engine Efficiency %	Fuel consumption g/kWh	Fuel consumption kg/trip
31.7	266	32

By considering the Marine Diesel emission factors (Table 15) it is possible to calculate the ferry boat emissions.

Table 15: Emission factors of the marine diesel²¹.

CO ₂ emission kgco ₂ /kg _{fuel}	SO _x emission Kgso _x /kg _{fuel}	NO _x emission kgNO _x /kg _{fuel}	Particulate emission kgppm/kg _{fuel}
3.206	0.00264	0.04896	0.00102

Moreover, by considering the weekly frequency of the ferry trips, it is possible to estimate the weekly ferry emissions (Figure 22) for the ferry boat operating with marine diesel. The reader should bear in mind that the emission calculation (conducted for this deliverable) does not take into consideration the harbour and manoeuvring phases; only navigation phase at constant speed has been considered. Additionally, the entire time of the trip, as assumption, has been considered as navigation time.

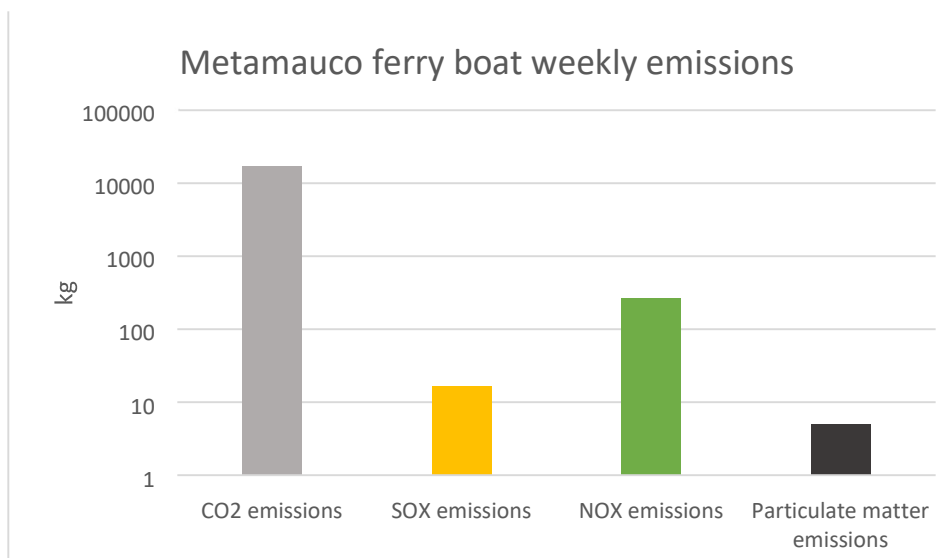


Figure 34. Ferry boat weekly emissions.

The required energy from the ferry is equal to 120 kWh for one trip. To calculate the required amount of hydrogen in a scenario of application of fuel cell powered ferries, the model follows an approach similar to the one presented for the internal combustion engine. From the experimental data of a fuel cell, suitable for maritime applications, the polynomial regression equation has been obtained and then a fuel cell efficiency equal to 51% has been obtained.

By considering the LHV of the hydrogen equal to 33.3 kWh/kg, the model determines a hydrogen consumption of 7 kg every trip. This means a weekly hydrogen consumption equal to 1176 kg, for the Metamauco ferry boat. As a good approximation, it is possible to consider that the emissions presented through Figure 22 are the avoided emissions for a scenario where the ferry boat is fully powered by hydrogen.

Croatian regional route – Split-Supetar

The seaport of Split (Figure 23) is a vital hub in the Adriatic Sea, serving as a key connection between the mainland and the Dalmatian²² islands. Located along the central Dalmatian coast, this busy port facilitates passenger, vehicles, and cargo transport, supporting the economy and tourism of the region. The port of Split offers regular ferry routes to several regional islands such as Hvar, Brač, and Vis, as well as international routes to Italy. Its infrastructure includes modern terminals, allowing efficient control of maritime traffic. The proximity of the port to Split's historic old town, a UNESCO World Heritage site, makes it a touristic hotspot for cultural and historical exploration.

²² Dalmatia is one of the four historical regions of Croatia, along with Central Croatia, Slavonia, and Istria.

Italy – Croatia



The seaport of Supetar (Figure 35), located on the northern coast of Brač Island in Croatia, is a key entry point and transport hub connecting the island to the mainland. This attractive port serves as the main ferry terminal for routes to Split, making it a vital link for passengers, vehicles, and goods. Surrounded by the charming town of Supetar, the port provides easy access to the island's stunning beaches, olive groves, and traditional Dalmatian architecture. The seaport also caters to smaller boats and yachts, offering a range of services for maritime visitors exploring the Brač island.

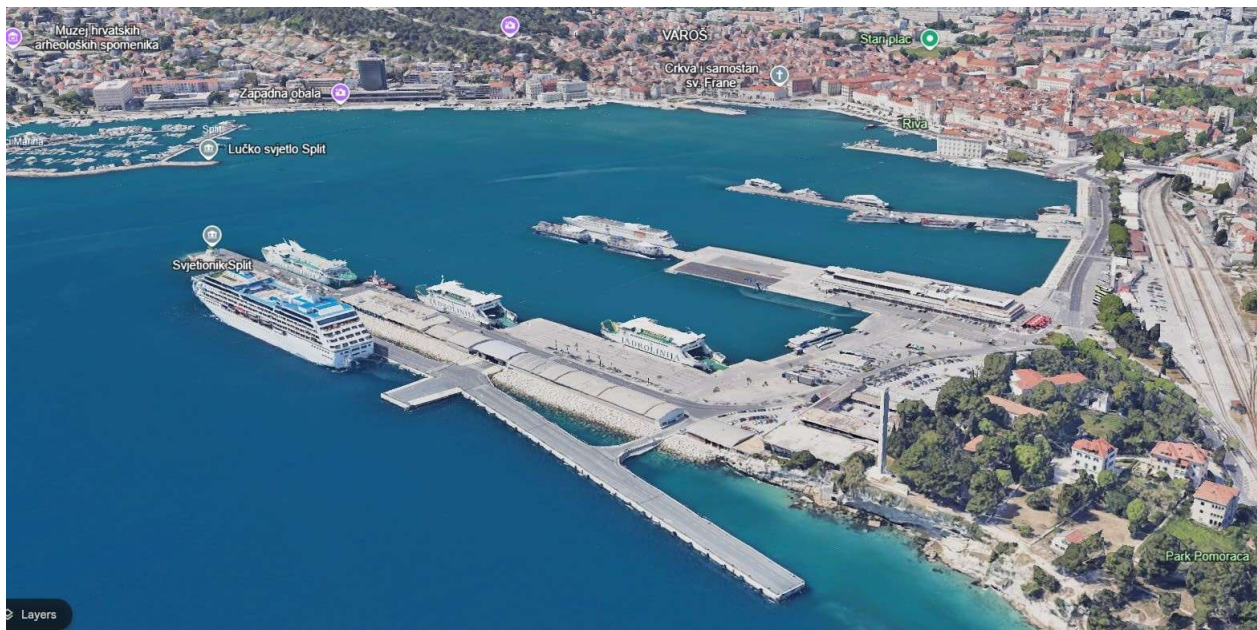


Figure 35. Port of Split (Luka Split d.d.) and ferry terminal (source: Google Earth).



Italy – Croatia



TransH2

Figure 36. Port of Supetar, Brač Island (source: Google Earth).

The maritime route between Split and Supetar is performed by using ferry boats such as the Hrvat (Figure 37) passenger/Ro-Ro cargo ship, operated by Jadrolinija, which is the Croatia's largest ferry company, operating an extensive fleet that connects the mainland to over 50 islands along the Adriatic coast.



Figure 37. Hrvat RO-RO vessel operated by Jadrolinija.

Environmental analysis

As explained in the section 1.1, the environmental evaluation is performed in terms of air quality assessment and considerations regarding the Natura 2000 sites.

Air quality

A platform developed by the Ministry of Environmental Protection and Green Transition of Croatia allows the user to see all the air quality monitoring stations throughout the country, as well as a considerable amount of data regarding the measurement of several types of air quality parameters. Figure 38 shows the monitoring stations in the region of Split.

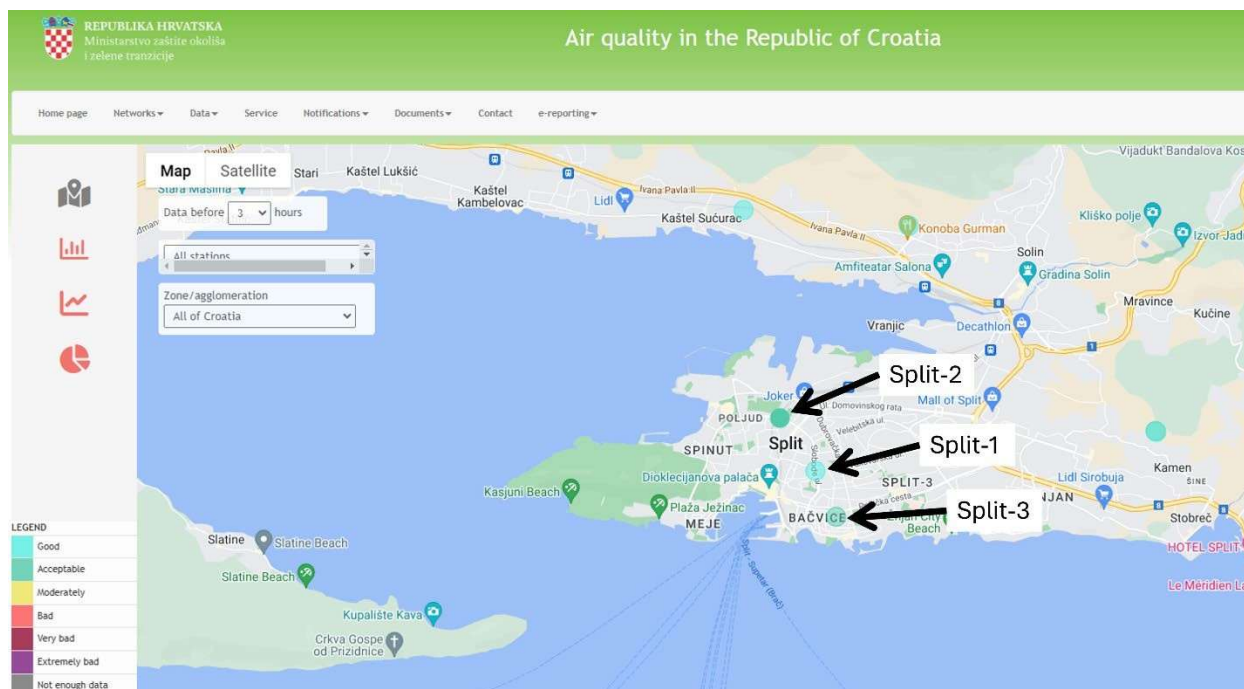


Figure 38. Platform issued by the Croatian Ministry of Environmental Protection and Green Transition, showing the air quality monitoring stations in the region of Split.

Sulphur dioxide (SO₂)

In 2023, the Croatian air quality assessment concerning SO₂ concentrations has been conducted based on data from nine monitoring stations, including two in the Split region (Split-1 and Split-3). According to the Report on Air Quality Monitoring in the Territory of the Republic of Croatia for the year 2023²³, SO₂ levels are regulated by strict limits: hourly concentrations must not exceed 350 µg/m³ more than 24 times a year, and daily averages must not surpass 125 µg/m³ more than three times annually. Additionally, an alert threshold of 500 µg/m³ applies when exceeded for three consecutive hours. The analysis confirmed that all zones in Croatia (including in the Split region, see Figure 27) complied with SO₂ limits in 2023, categorizing the air as Class I quality. No exceedances were recorded for either hourly or daily limits, ensuring compliance with health protection standards.

²³ <https://iszz.azo.hr/iskzl/godizvrpt.htm?pid=0&t=0>

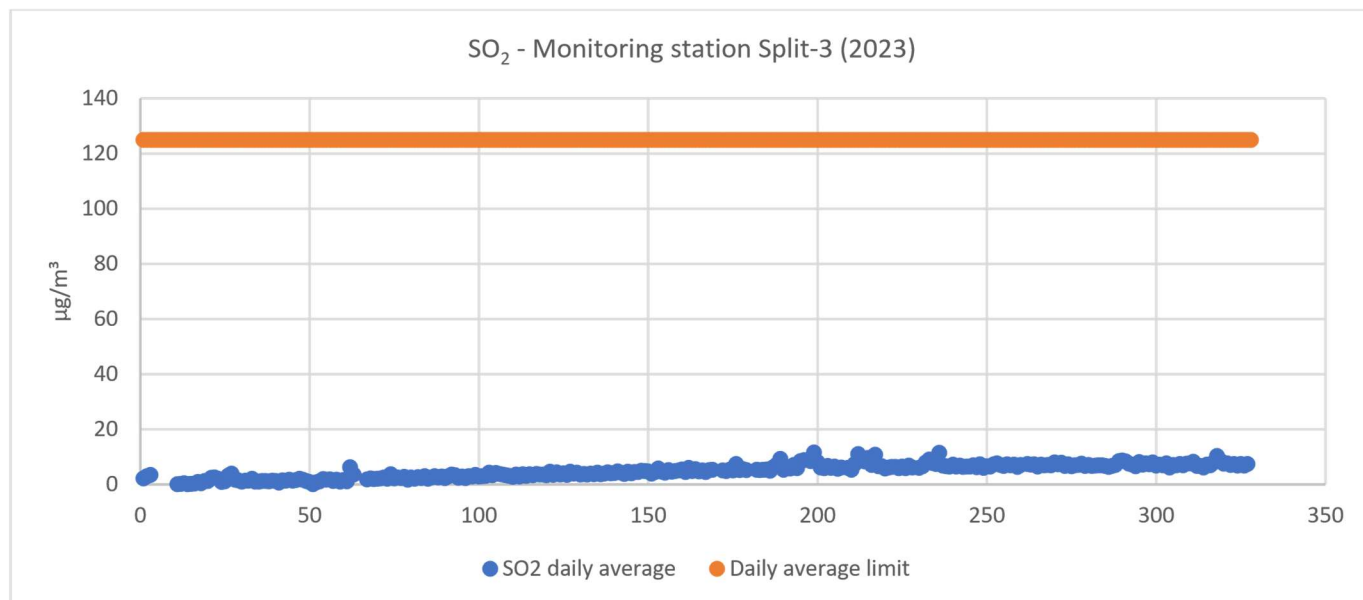


Figure 39. Daily average for SO_2 measurements in the Split-3 monitoring station in 2023. Data collected from the platform shown in Figure 26.

Nitrogen dioxide (NO_2)

Measurements of NO_2 concentrations were analysed in order to assess air quality compliance with environmental targets in 2023 from 15 monitoring stations (including Split-1 and Split-3). According to the Report on Air Quality Monitoring in the Territory of the Republic of Croatia for the year 2023²⁴, one-hour NO_2 concentrations must not exceed the limit value of $200 \mu\text{g}/\text{m}^3$ more than 18 times in a calendar year, and the annual average concentration must not exceed $40 \mu\text{g}/\text{m}^3$ (as shown in Figure 28, for 2023). Additionally, an alert threshold of $400 \mu\text{g}/\text{m}^3$ is triggered if exceeded for three consecutive hours.

For what concern the Split-3 monitoring station, the analysis of 2023 data concluded that most of the daily average remained below the $40 \mu\text{g}/\text{m}^3$ daily threshold, with only one event over that limit on July. In fact, as observed in Figure 28, most of the daily averages remained below $30 \mu\text{g}/\text{m}^3$, with only a few values between 30 and $40 \mu\text{g}/\text{m}^3$. However, and still according to the mentioned report, most of the daily averages concentrations were at or above the World Health Organization's recommended limit of $10 \mu\text{g}/\text{m}^3$.

²⁴ <https://iszz.azo.hr/iskzl/godizvrpt.htm?pid=0&t=0>

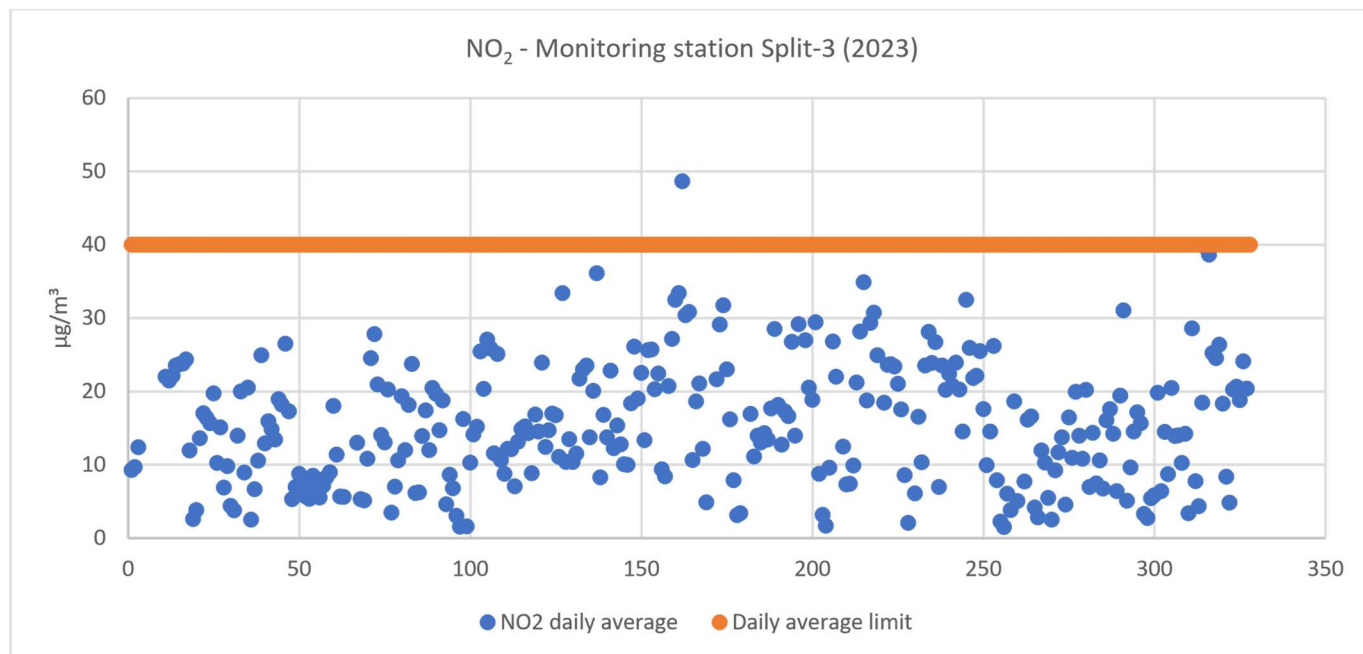


Figure 40. Daily average for NO₂ measurements in the Split-3 monitoring station in 2023. Data collected from the platform shown in Figure 26.

NO₂ concentrations vary daily, weekly, and seasonally due to its chemical and physical properties, population activity, and meteorological conditions. Peak concentrations are typically observed in the morning and evening, coinciding with commute times, reflecting its connection to traffic emissions. Figure 40 also reveals some peak events during the summer, which reflects also the intensification of the traffic flow during this period.

Carbon monoxide (CO)

The air quality monitoring data for CO (Figure 29) was collected from the Split-2 monitoring station. According to the Report on Air Quality Monitoring in the Territory of the Republic of Croatia for the year 2023, the maximum daily average CO concentration must not exceed the limit of 10 mg/m³ at any time during the year.

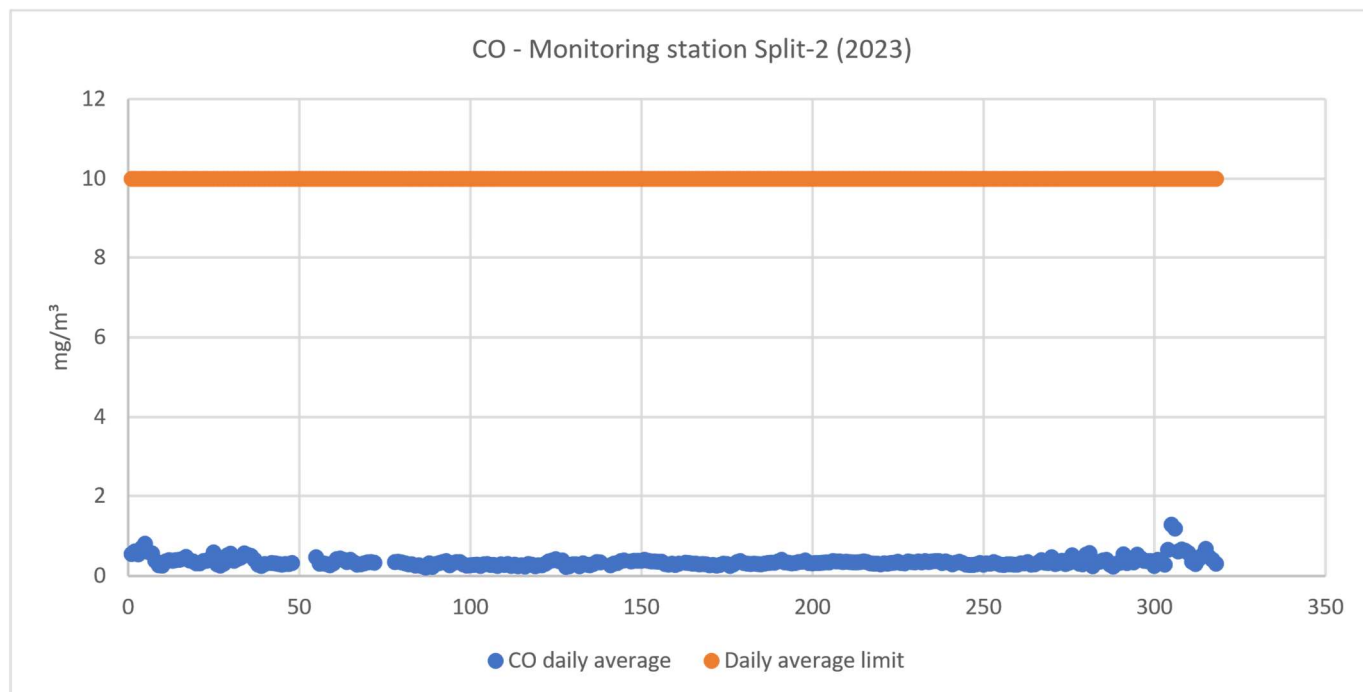


Figure 41. Daily average for CO measurements in the Split-2 monitoring station in 2023. Data collected from the platform shown in Figure 26.

Analysis of measurements and expert evaluations concluded that all Croatian zones complied with the CO limit in 2023, including the Split region.

Particulate matter (PM_{2.5} and PM₁₀)

According to the Report on Air Quality Monitoring in the Territory of the Republic of Croatia for the year 2023, daily **PM₁₀ concentrations** must not exceed 50 µg/m³ more than 35 days per year. In 2023, only one monitoring station in Croatia (Kutina-1) exceeded the daily limit on 37 days, making it non-compliant. However, all other zones, including the monitoring stations at Split, complied with the daily PM₁₀ limits. In fact, as observed on Figure 30, the data collected from the monitoring station Split-3 shows that the daily average PM₁₀ remained below the 50 µg/m³ threshold throughout the whole year, with most of the peaks over 30 µg/m³ happening during the summer.

Italy – Croatia



TransH2

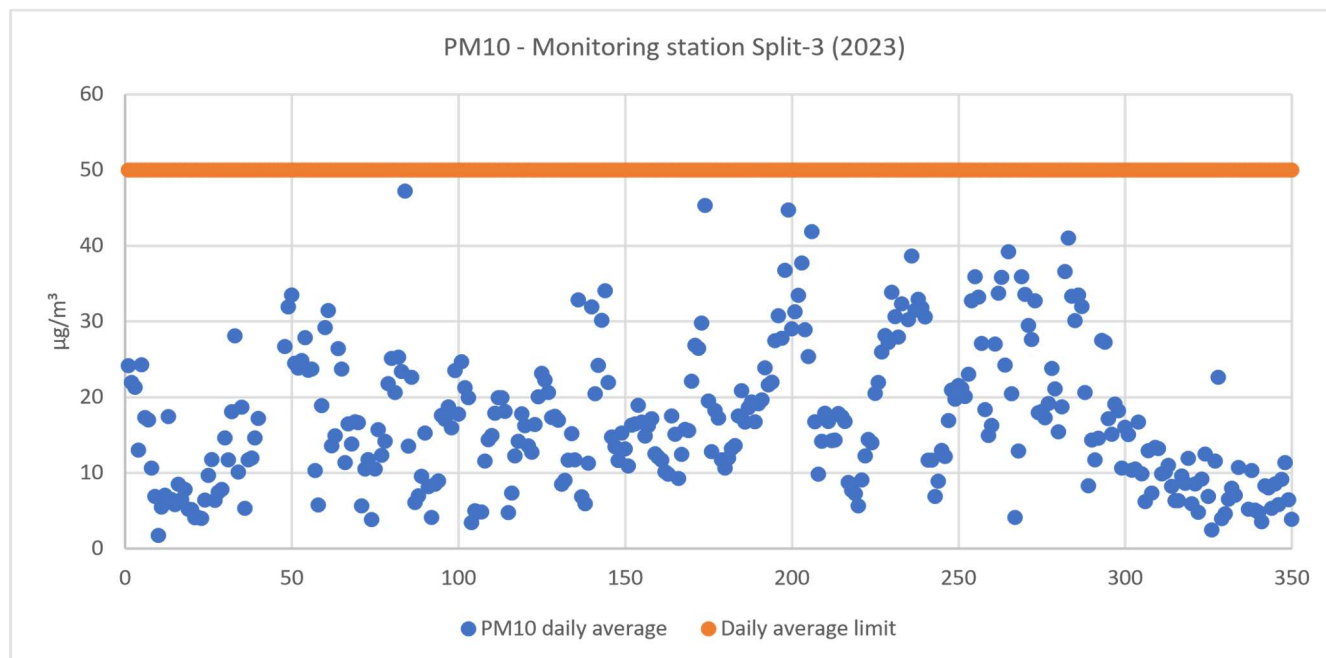


Figure 42. Daily average for PM10 measurements in the Split-3 monitoring station in 2023. Data collected from the platform shown in Figure 26.

For PM2.5, the daily average limit of $25 \mu\text{g}/\text{m}^3$ applies. According to the data collected from the Split-3 monitoring station, in 2023 the annual limit was exceeded for few times, while most of the values remained below $20 \mu\text{g}/\text{m}^3$. Despite compliance with legal thresholds, all stations reported concentrations exceeding the World Health Organization's recommended limit of $5 \mu\text{g}/\text{m}^3$.

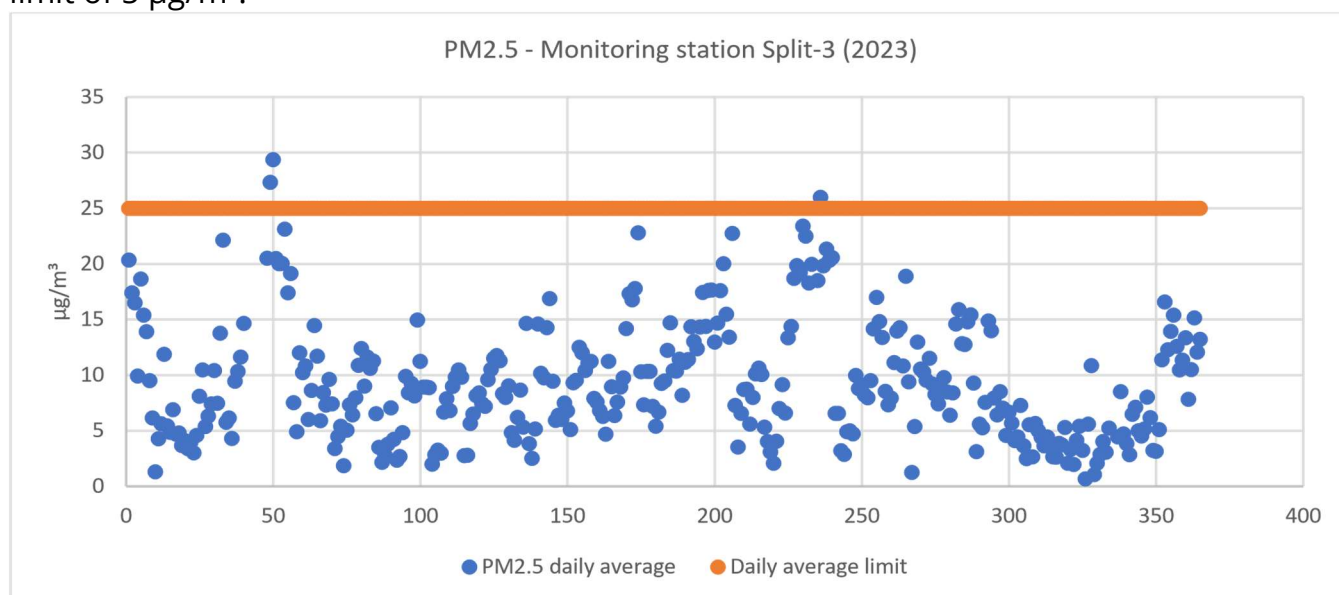


Figure 43. Daily average for PM_{2.5} measurements in the Split-3 monitoring station in 2023. Data collected from the platform shown in Figure 26.

Natura 2000 sites

The Dalmatian region, particularly the Split area, is surrounded by numerous sites protected under the Natura 2000 directives. As illustrated in Figure 44, both the mainland and nearby islands have areas designated under the Birds Directive, the Habitats Directive, or both. However, as shown in Figure 30(b), the Split-Supetar maritime route does not cross any Natura 2000 site. Despite this, the surrounding protected areas would certainly benefit from reduced emissions in a scenario where traditional dieselpowered ferry engines are replaced by hydrogen-powered systems, which produce zero emissions during operation.

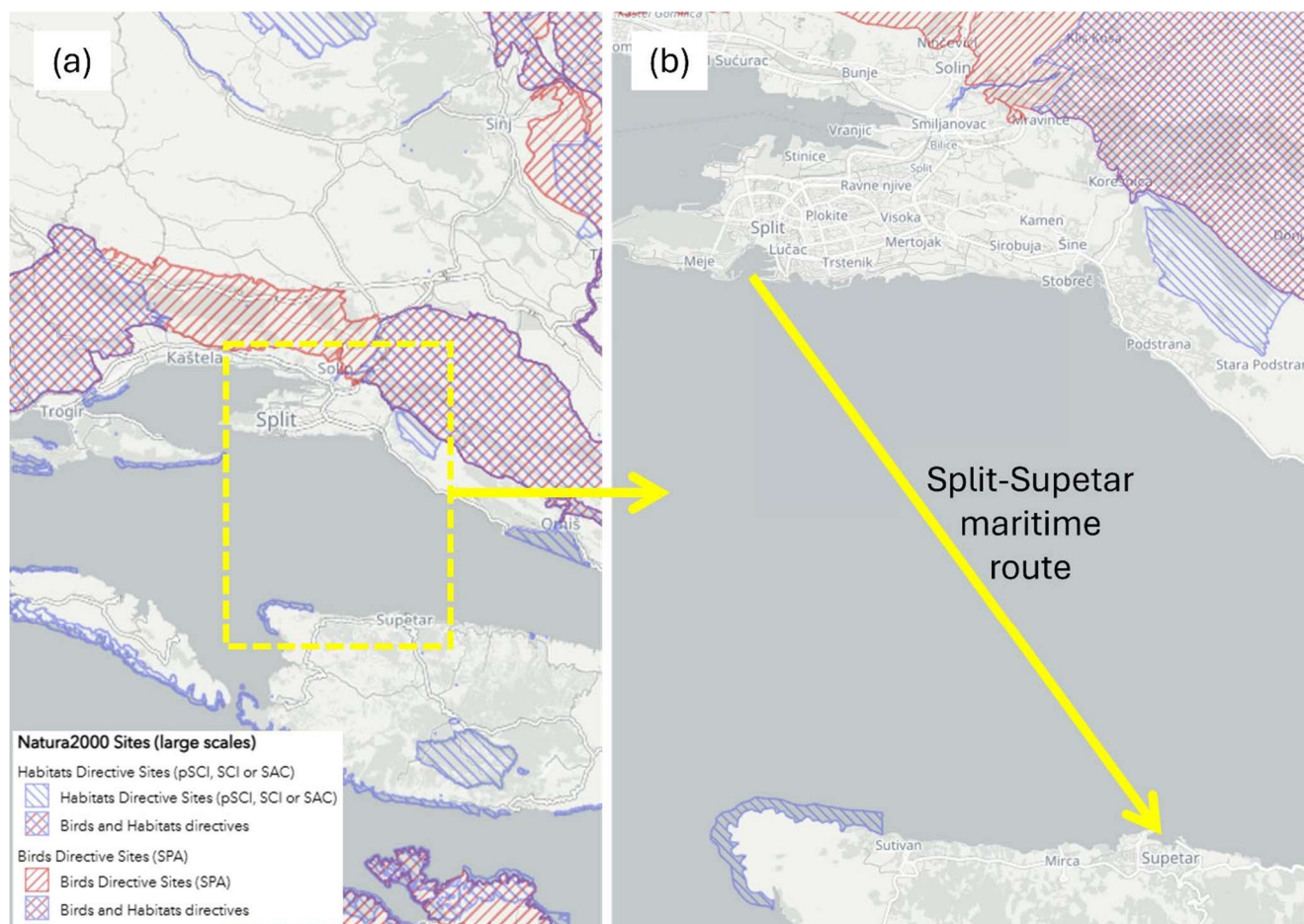


Figure 44. Natura 2000 in the region of Split.

Italy – Croatia



TransH2

Navigational analysis

The navigational analysis for the Split-Supetar maritime route is focused on two main aspects: the characteristics of the route (coordinates, length, and bathymetry) and the environment conditions (wind direction and velocity as well as waves direction and height).

Characteristics of the Split-Supetar maritime route

The coordinates of the two involved maritime ports are as follows:

- The Split ferry terminal is located at the latitude 43.503029° N and the longitude 16.440601° E.
- Supetar ferry terminal is situated at the latitude 43.385824° N and longitude 16.554806° E.

The length of the route is approximately 16 km (10 Nautic Miles). The ferry service operates between the two terminals, typically taking between 45 to 50 minutes to complete one-way journey.

The ocean region between Split Port and Supetar Port presents a relatively shallow and uniform bathymetry, which is a characteristic of the eastern Adriatic Sea. According to the Bathymetric Data Viewer²⁵, provided by the American National Oceanic and Atmospheric Administration (NOAA), The seafloor depth along this maritime route ranges between 10 to 50 meters (as seen in Figure 45), with some variations influenced by natural seabed formations and underwater currents.

²⁵ <https://www.ncei.noaa.gov/maps/bathymetry/>



Figure 45. Bathymetry concerning the Split-Supetar maritime route area.

Meteorological and oceanographic conditions

As stated in the beginning of section 4.2, the meteorological analysis of this report is focused on the wind conditions of the region under analysis, while the oceanographic analysis is focused on the wave conditions of the region under analysis.

Wind speed and direction analysis

Figure 46 presents the wind speed and direction for several monitoring stations in Croatia, including the

Italy – Croatia



TransH2

Split-Marjan station in the region of Split. The data is part of the Climate Atlas of Croatia, issued by the Croatian Meteorological and Hydrological Service²⁶, and represent the annual average data regarding the period between 1981 and 1990. As observed, the Split zone has a predominance of wind (almost 30% of the time) from the North-Northeast (NNE) direction, with speed levels over 5.4 m/s. The Split-Marjan wind-rose also highlights the directions East-Southeast (ESE) and South-Southwest (SSW): around 15% of the time the wind blew from the ESE direction under speed ranges reaching over 5.4 m/s; also, the wind blew from the SSW direction for about 12% of the time under a speed range between 0.3 and 5.4 m/s most of the time.

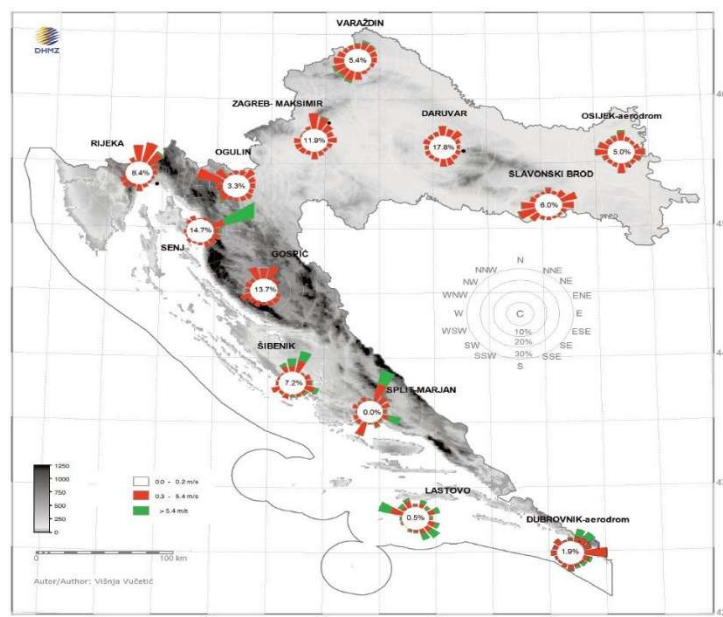


Figure 46. Wind speed and direction for Croatia. Annual average for the period 1981-1990.

Wave height and direction analysis

Since no official open-source data have been found, the present wave analysis has been based on the scientific literature. A scientific work (developed by the Croatian Hydrological and Meteorological Service and The Faculty of Civil Engineering, University of Zagreb) has been selected as a representative study involving the wave behaviour specifically in the region between the ports of Split and Supetar. The work²⁷ (Berbić, J. et al, 2017), which focused on the application of a specific methodology for wave height prediction, analysed real data collected in two specific points of the Adriatic Sea. One of these points is what the authors called “V2” (using a Datowell waverider, type MKIII) and was located off shore Split town, in the coordinates 43°29.3' latitude and 16°27.9' longitude (Figure 47).

²⁶ Croatian Meteorological and Hydrological Service. https://meteo.hr/klima_e.php?section=klima_hrvatska¶m=k1_7

²⁷ Berbić, J., Ocvirk, E., Carević, D., & Lončar, G. (2017). Application of neural networks and support vector machine for significant wave height prediction. *Oceanologia*, 59(3), 331-349. <https://doi.org/10.1016/j.oceano.2017.03.007>



Figure 47. Location of the V2 waverider, as specified by Berbić, J. et al, (2017).

Still according to the same authors, a comparison between the measured waverider data and a simulated time series (both for wave heights) has been performed for the period between November 1st, 2007 to November 15th, 2008, which is presented through Figure 36. As observed, the maximum wave height did not exceed 1.5 meters for the whole analysed period. No data for wave direction have been reported by the authors.

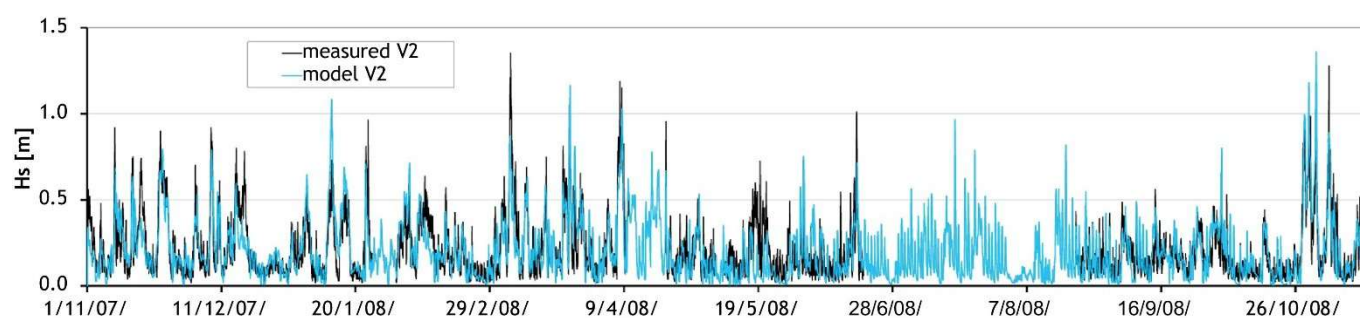


Figure 48. Comparison of the measured and modelled time series of wave heights at the waverider station V2 during the period from 01/11/2007 to 15/11/2008 (Berbić, J. et al, 2017).

Transportation analysis

Based on the calculations performed for the Tronchetto-Lido maritime route (section 3.3), it is also possible to estimate the fuel consumption and related emissions for the ferry boat operating in the SplitSupetar maritime route. Table 16 introduces the main characteristics of the ferry boat Hrvat (Figure 25) while Table 16 introduce the characteristics of the route.

Table 16: Characteristics of the Hrvat ferry boat (Figure 25).

Italy – Croatia

TransH2

Main engine (MW)	Max speed (kn)	Length Overall (m)	Engine Type	Beam (m)	Draught (m)	Depth (m)	Deadweight (t)
2.14	13	87.6	4 X CAT 3412 DITA	18	2.4	3.7	569

Table 17: Characteristics of the Split-Supetar ferry route.

Frequency (times/week)	Distance (NM)	Travel time (h)	Service speed (knots)
61-98	10	0.83	11.5

By following the same considerations presented in the Tronchetto–Lido route, it is possible to estimate the ferry engine power, the engine efficiency, and the fuel consumption during ferry navigation (Table 17). Due to the missing data regarding the CAT 3412 DITA marine engine, the calculations performed for the Split-Supetar maritime route is based on the same engine used for the Tronchetto-Lido maritime route (Table 18).

Table 18: Main results of the tool based for one trip for the ferry boat Hrvat.

Engine power kW	Engine Efficiency %	Fuel consumption g/kWh	Fuel consumption kg/trip
1487	38	222	274

By considering the weekly frequency of the ferry trips, it is possible to calculate the weekly ferry emissions (Figure 49), for the ferry boat operating with marine diesel. In this figure, it is possible to see a slight difference between low and high seasons due to the highest weekly frequency of the ferry route in the high season. The reader should bear in mind that the emission calculation (conducted for this deliverable) does not take into consideration the harbour and manoeuvring phases; only navigation phase at constant speed has been considered. Additionally, the entire time of the trip, as assumption, has been considered as navigation time.

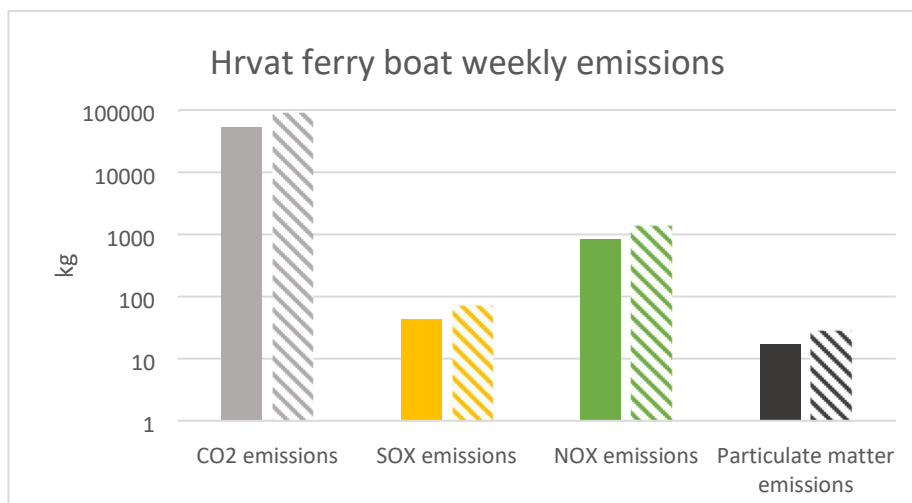


Figure 49. Hrvat ferry boat weekly emissions (for low and high seasons).

The required energy from the ferry is equal to 1234 kWh for one trip. By considering a fuel-cell-powered ferry boat, with a 50% efficiency fuel cell, it is possible to obtain a hydrogen consumption of 74 kg per trip. The calculation, based on the assumption presented in the previous case Tronchetto-Lido, leads to a hydrogen weekly utilization of 4514 kg in low season and 7252 kg in high season. As a good approximation, it is possible to consider that the emissions presented through Figure 37 are the avoided emissions for a scenario where the ferry boat is fully powered by hydrogen.

Cross-border route – Ancona-Split

The Port of Ancona (Figure 38) is located in the homonym Italian city, in the region of Marche, it is one of the most important maritime hubs for the country. Serving as a critical gateway for trade of goods and passenger transport, it connects Italy to several countries including Croatia, Greece, and other Balkan countries. Its history as a port dates back to the ancient Roman period, showcasing centuries of maritime tradition and development. The port handles diverse types of cargo, including containers, petroleum products, and bulk materials, while also supporting the fishing industry. Ancona is a major embarkation point for ferries, welcoming a significant number of passengers annually.

The port of Split has already been described in this report and, for that reason, the reader is invited to go back to section 4.

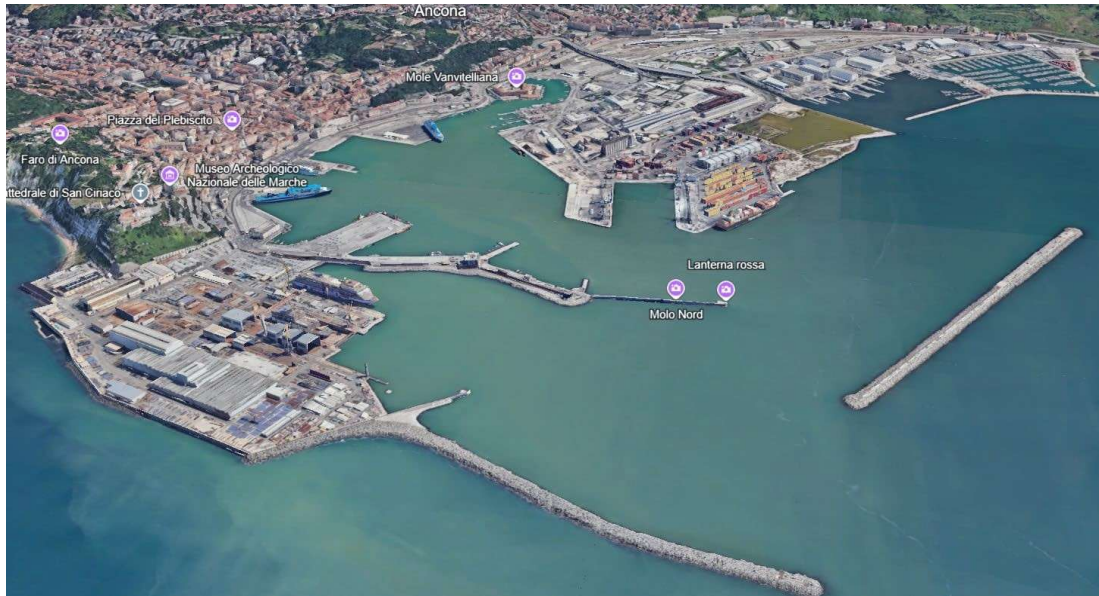


Figure 50. Port of Ancona (source: Google Earth).

The maritime route between Ancona and Split is performed by using ferry ships such as the Marko Polo (Figure 51) passenger/Ro-Ro cargo ship, operated by Jadrolinija, which is the Croatia's largest ferry company, operating an extensive fleet that connects the mainland to over 50 islands along the Adriatic coast.



Figure 51. Passenger/Ro-Ro cargo ship, operated by Jadrolinija.

Environmental analysis

As explained in the section 1.1, the environmental evaluation is performed in terms of air quality assessment and considerations regarding the Natura 2000 sites.

Air quality

The air quality monitoring in the Marche region is managed by ARPAM (Agenzia Regionale per la Protezione Ambientale delle Marche or Marche Regional Agency for Environmental Protection), which owns a dedicated web platform for monitoring the regional air quality. Figure 52 presents a screenshot of the platform and shows the exact location of the monitoring station called “Ancona Cittadella”, which is the one from where the data of this section has been taken.

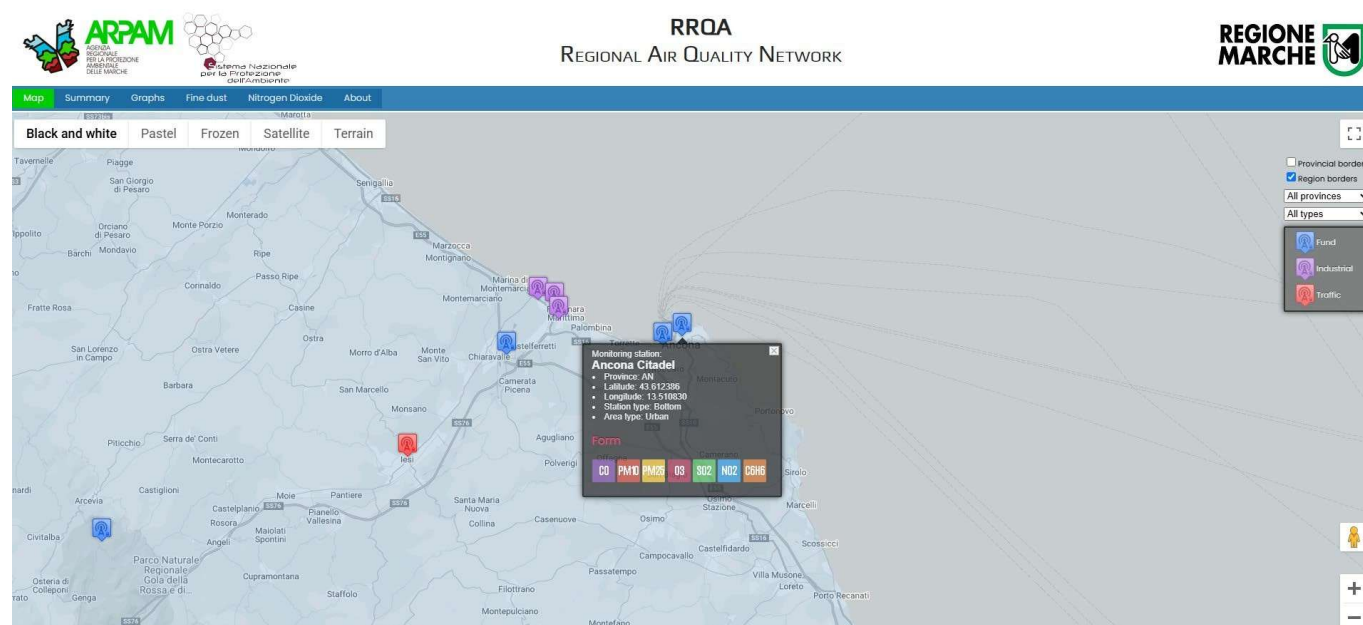


Figure 52. Regional air quality network platform developed by the Italian region where Ancona is located²⁸.

Sulphur dioxide (SO₂)

The daily average SO₂ concentrations, measured by the Ancona Cittadella monitoring station in 2023, are shown in Figure 41. According to the air quality report issued by ARPAM in 2023²⁹, the daily limit for

²⁸ <https://aria.arpa.marche.it/Default.aspx>

²⁹ <https://www.arpa.marche.it/indicatori-ambientali?id=1510>



human protection is $125 \mu\text{g}/\text{m}^3$. As observed, the measured values are well below the established threshold, indicating the conformity of SO_2 concentrations in the region where the port of Ancona is located.

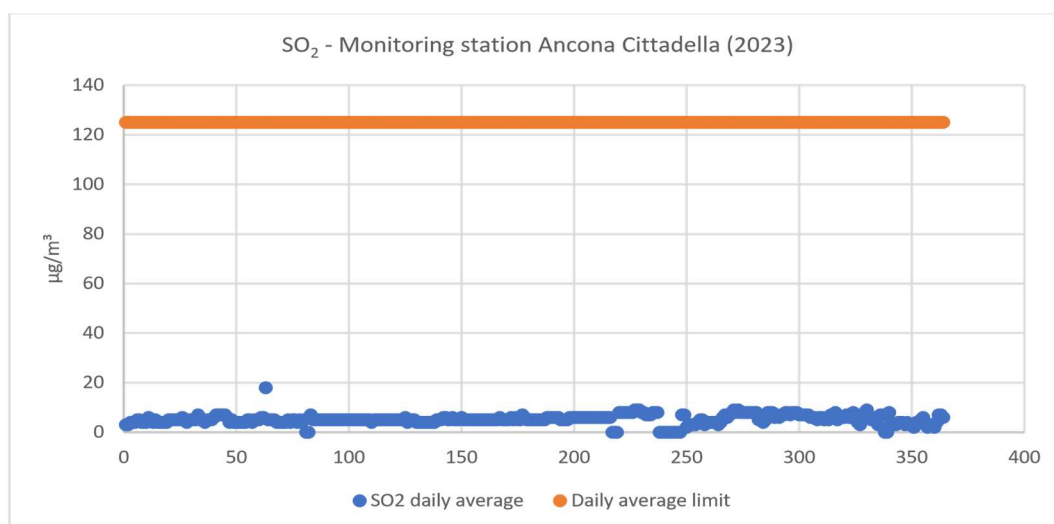


Figure 53. Daily average for SO_2 measurements in the Ancona Cittadella monitoring station in 2023. Data collected from the platform shown

in Figure 52.

Nitrogen dioxide (NO_2)

The daily average NO_2 concentrations, measured by the Ancona Cittadella monitoring station in 2023, are shown in Figure 42. According to the air quality report issued by ARPAM in 2023, the daily limit for human protection is $40 \mu\text{g}/\text{m}^3$. As observed, the measured values are below the established threshold most of the time, with an annual average around $18 \mu\text{g}/\text{m}^3$. Although there is an increasing in the seaborne passenger flow passing through the Ancona port during the summer, the data shows higher concentration levels in the winter period.

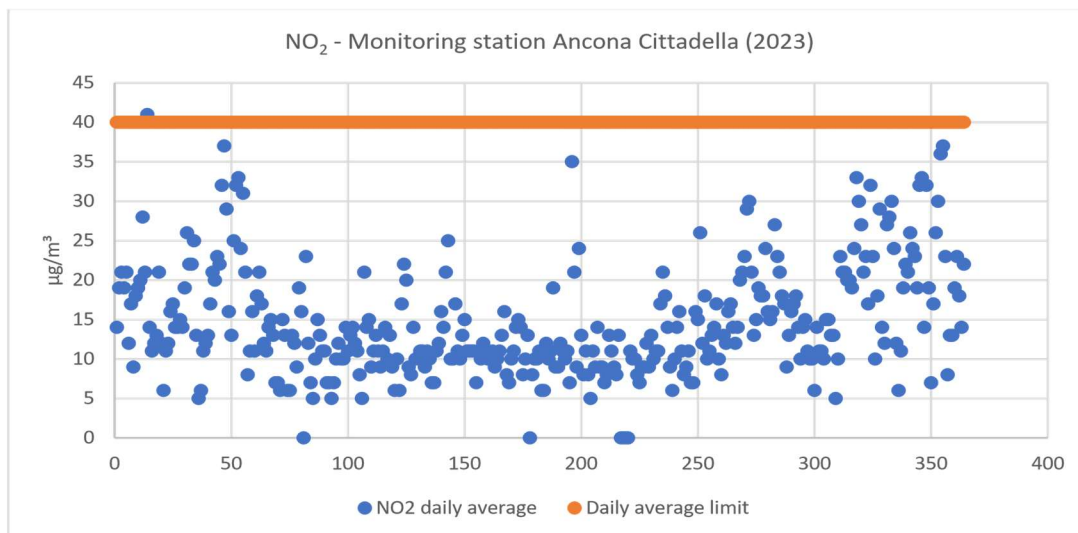


Figure 54. Daily average for NO₂ measurements in the Ancona Cittadella monitoring station in 2023. Data collected from the platform shown in Figure 40.

Carbon monoxide (CO)

The daily average CO concentrations, measured by the Ancona Cittadella monitoring station in 2023, are shown in Figure 43. According to the air quality report issued by ARPAM in 2023, the daily limit for human protection is 10 mg/m³. As observed, the measured values are well below the regulated established threshold.

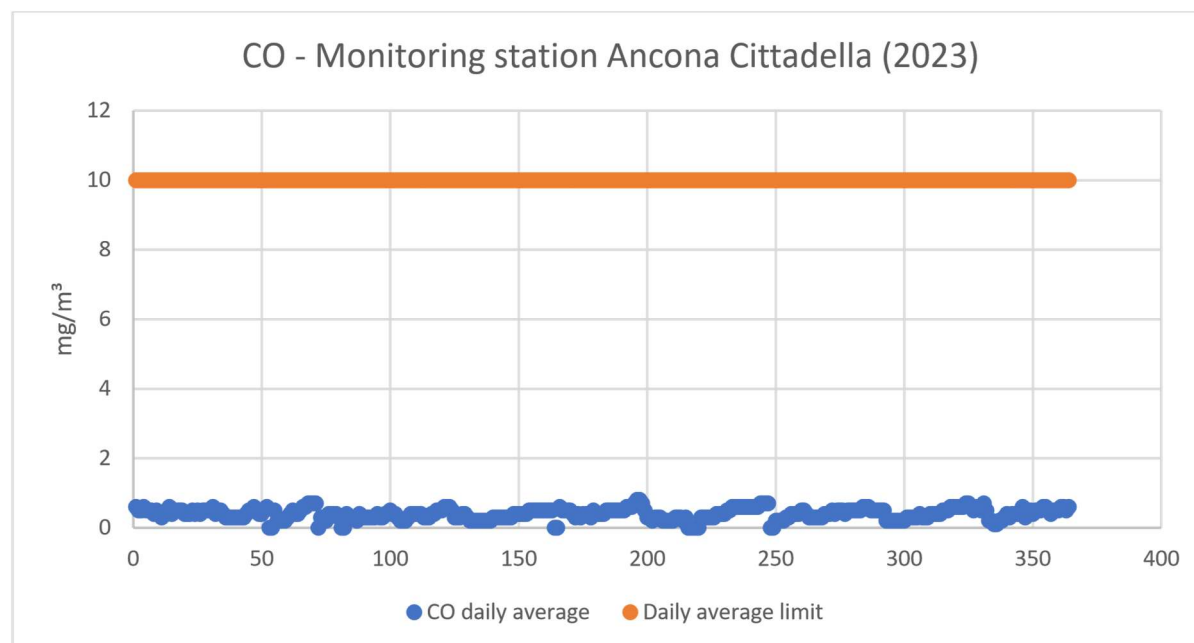


Figure 55. Daily average for CO measurements in the Ancona Cittadella monitoring station in 2023. Data collected from the platform shown in Figure 40.

Particulate matter (PM2.5 and PM10)

The analysis of PM concentrations measured by the Ancona Cittadella monitoring station highlights the seasonal variations influenced by atmospheric conditions and emission sources. PM levels are typically higher in winter, driven by poor pollutant dispersion and increased emissions from heating systems and other sources. The regulatory annual average limit for PM10 and PM2.5 are 40 $\mu\text{g}/\text{m}^3$ and 20 $\mu\text{g}/\text{m}^3$, respectively.

Annual average **PM10 concentrations** for 2023 (Figure 44) show a group of peak values during the winter and summer periods. During the summer, the measured values remained below the established threshold, however, some of the winter peak values resulted above the limit.

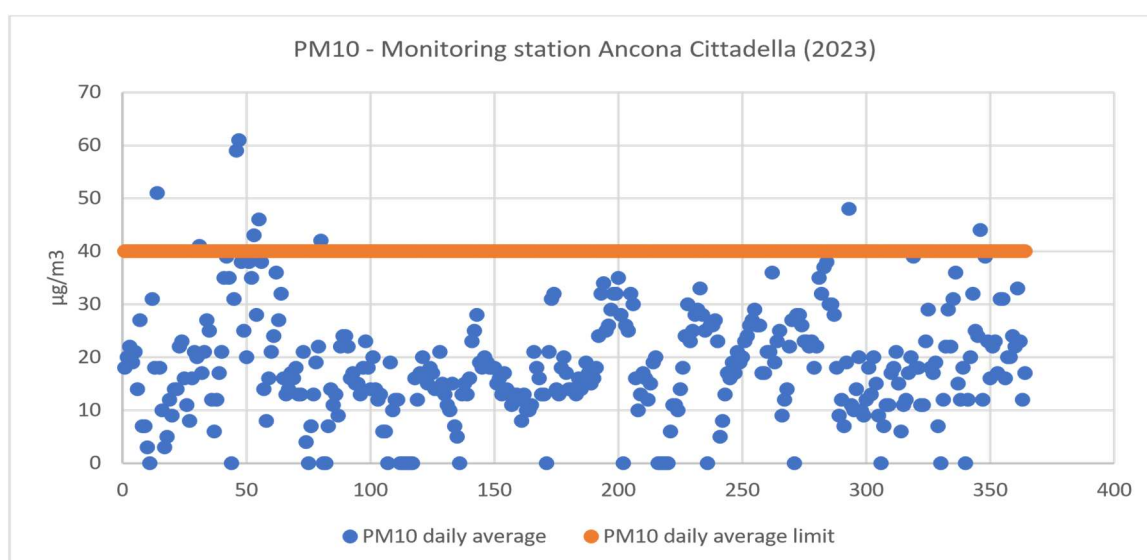


Figure 56. Daily average for PM10 measurements in the Ancona Cittadella monitoring station in 2023. Data collected from the platform shown in Figure 40.

The **PM2.5** trend for 2023, aligns closely with that of PM10. However, both the winter and summer peak values resulted above the established annual limit of 20 $\mu\text{g}/\text{m}^3$. Such fact can be attributed to not only heating systems (in winter), but also to a higher activity level in the port of Ancona.

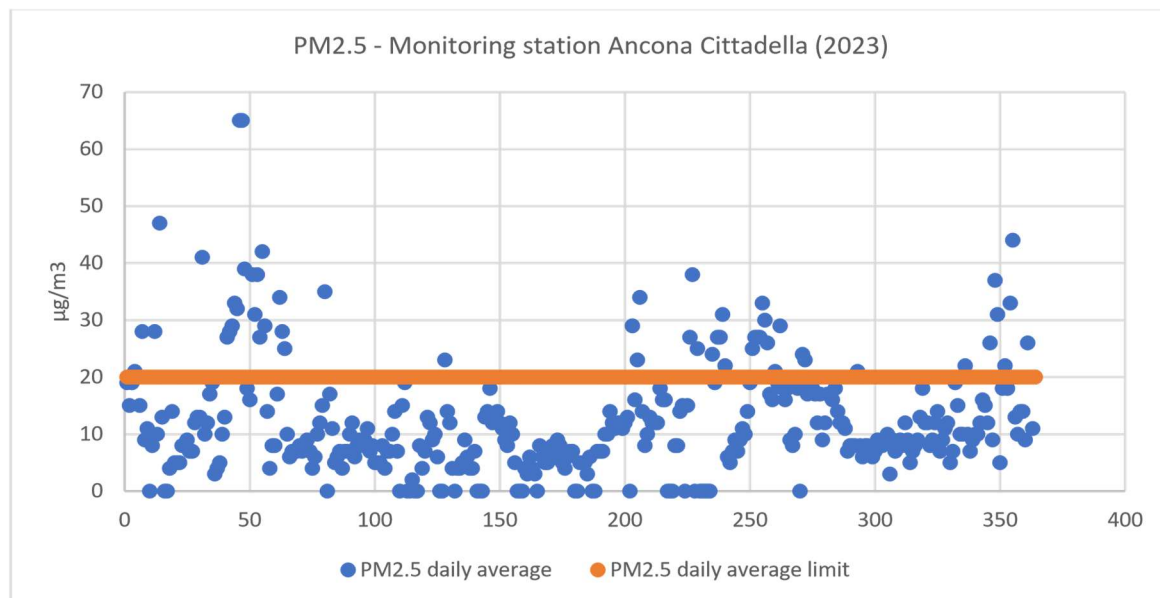


Figure 57. Daily average for PM2.5 measurements in the Ancona Cittadella monitoring station in 2023. Data collected from the platform shown in Figure 52.

Natura 2000 sites

The region of the Ancona port does not have any area designated under the Natura 2000 directives. There is, however, an area to the south of the Ancona city (Figure 46) of about 20 km², which is under both the Birds and Habitats directives. It should be noted that, the Ancona-Split route does not cross the mentioned Natura 2000 site, however it would certainly benefit from the emissions reduction resulted from the implementation of hydrogen powered systems for the vessels under analysis within this project.

When crossing the Adriatic Sea, the Ancona-Split route does not cross any Natura 2000 site. Moreover, as observed in Figure 58, when approaching the Croatian coast, on the way to the Split port, the AnconaSplit route also does not pass through any Natura 2000 site, although its trajectory crosses a region with several areas Natura 2000 sites nearby, specifically, sites under the Habitats directive.

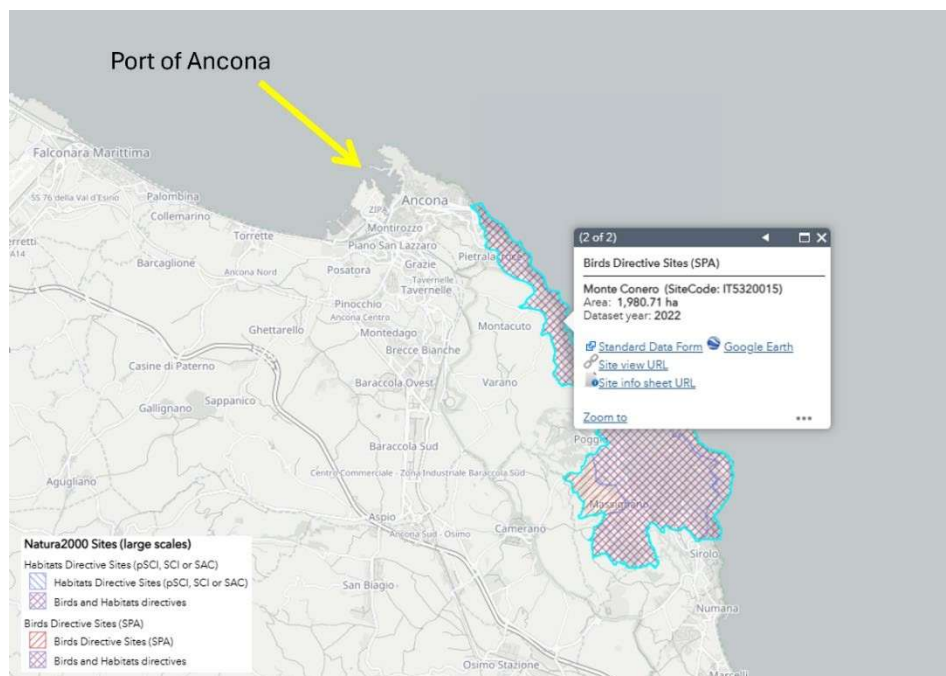


Figure 58. Natura 2000 site near the port of Ancona.

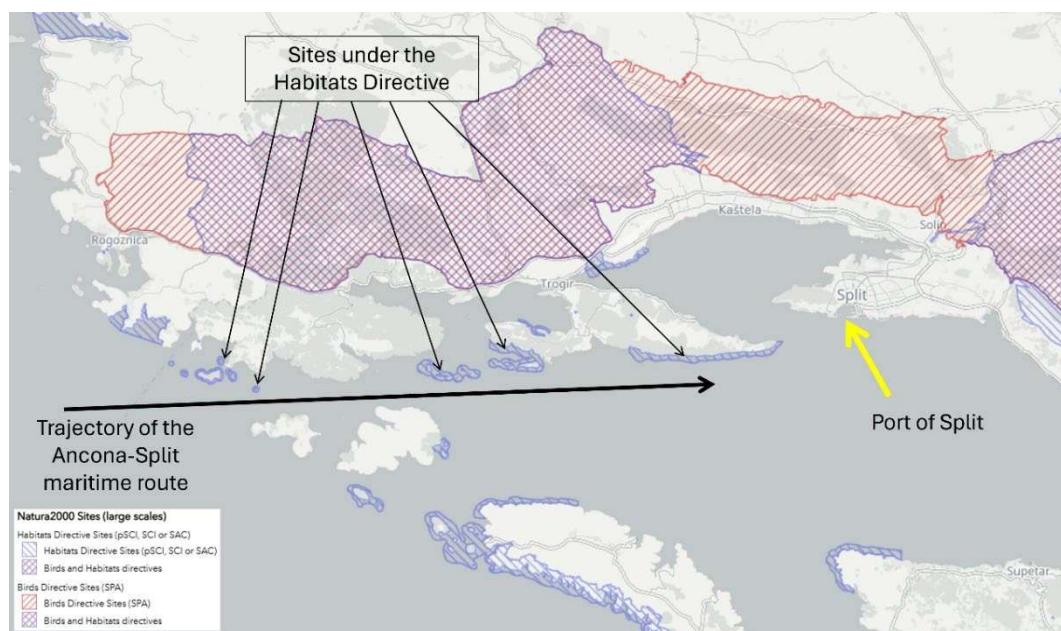


Figure 59. Natura 2000 site near the port of Split.

Navigational analysis

The navigational analysis for the Ancona-Split maritime route is also focused on two main aspects: the characteristics of the route (coordinates, length, and bathymetry) and the environment conditions (wind direction and velocity as well as waves direction and height).

Characteristics of the Ancona-Split maritime route

The coordinates of the two involved maritime ports are as follows:

- The Ancona Port is located at the latitude 43.620892° N and the longitude 13.507311° E.
- The Split ferry terminal is located at the latitude 43.503029° N and the longitude 16.440601° E.

The length of the route is approximately 240 km (129 Nautic Miles). The ferry service operates between the two terminals, typically taking between 8 to 11 hours to complete one-way journey. The ocean region between Ancona port and Split port presents a wider range of depths. According to Berbić, J. et al. (2017)³⁰, the seafloor depth along this maritime route ranges between 10 to 400 meters (Figure 48).

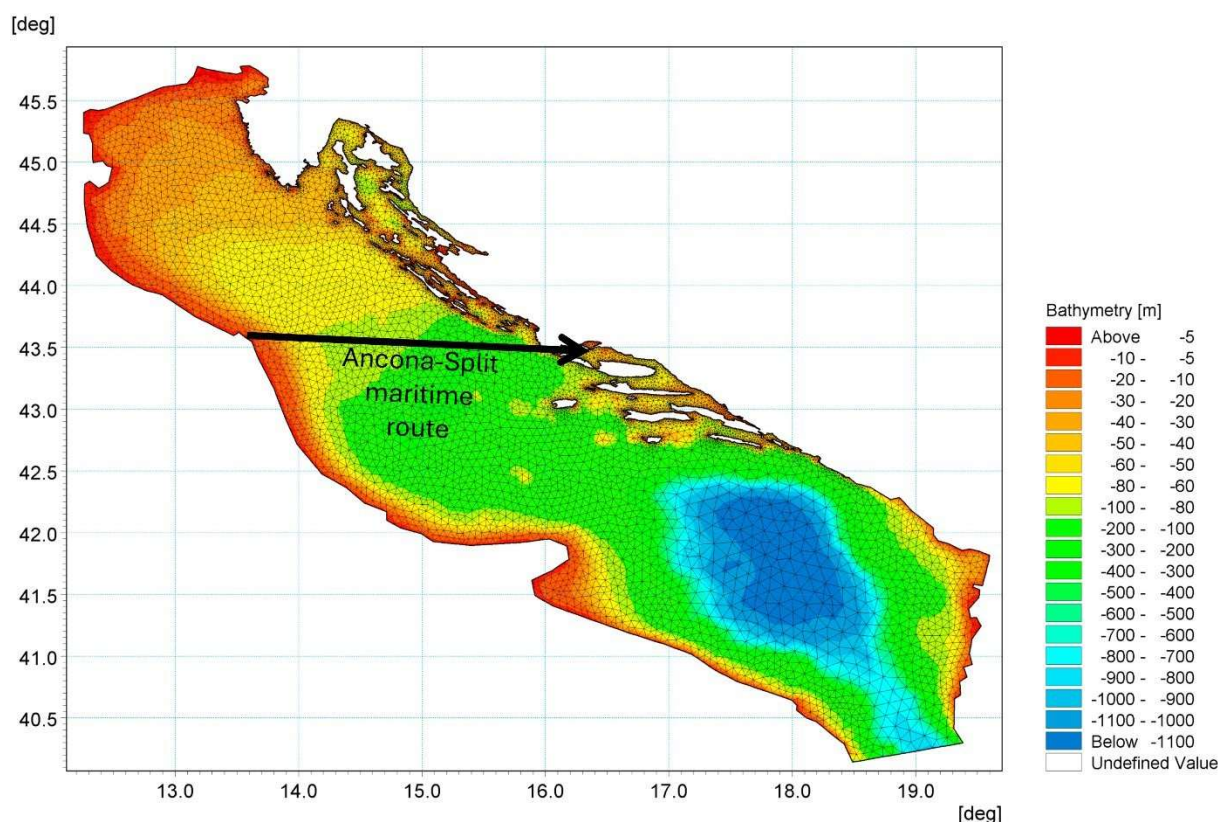


Figure 60. Adriatic Sea bathymetry and the Ancona-Split route. Graphic adapted from Berbić, J. et al, (2017).

³⁰ Berbić, J., Ocvirk, E., Carević, D., & Lončar, G. (2017). Application of neural networks and support vector machine for significant wave height prediction. *Oceanologia*, 59(3), 331-349. <https://doi.org/10.1016/j.oceano.2017.03.007>

Meteorological and oceanographic conditions

As stated in the beginning of section 5.2, the meteorological analysis of this report is focused on the wind conditions of the region under analysis, while the oceanographic analysis is focused on the wave conditions of the region under analysis. All the data presented in this section has been collected in the ISPRA website³¹.

Wind speed and direction analysis

Figure 49 presents the annual average wind speed and direction for the region of Ancona in the years of 2013, 2014, 2019, and 2023. As seen, the wind direction pattern has not varied significantly in the past 10 years. For the four selected years, there is a predominance of wind coming from the Southeast (SE) and Southwest (SW) directions, with a speed range varying from about 0.2 to 14 m/s.

In order to have an idea about the wind behaviour within a single year, Figure 61 provides the average wind speed and direction for the Winter, Spring, Summer, and Autumn of 2023. As observed, in fact there is a predominance of wind from the SW and West-Southwest (WSW) direction during the Winter, while for all the other seasons there is a predominance of wind coming not only from SW but also from Southeast (SE).

³¹ ISPRA – *Istituto Superiore per la Protezione e la Ricerca Ambientale* or Superior Institute for Environmental Protection and Research (<https://www.mareografico.it/en/stations-comparison.html>)

Italy – Croatia



TransH2

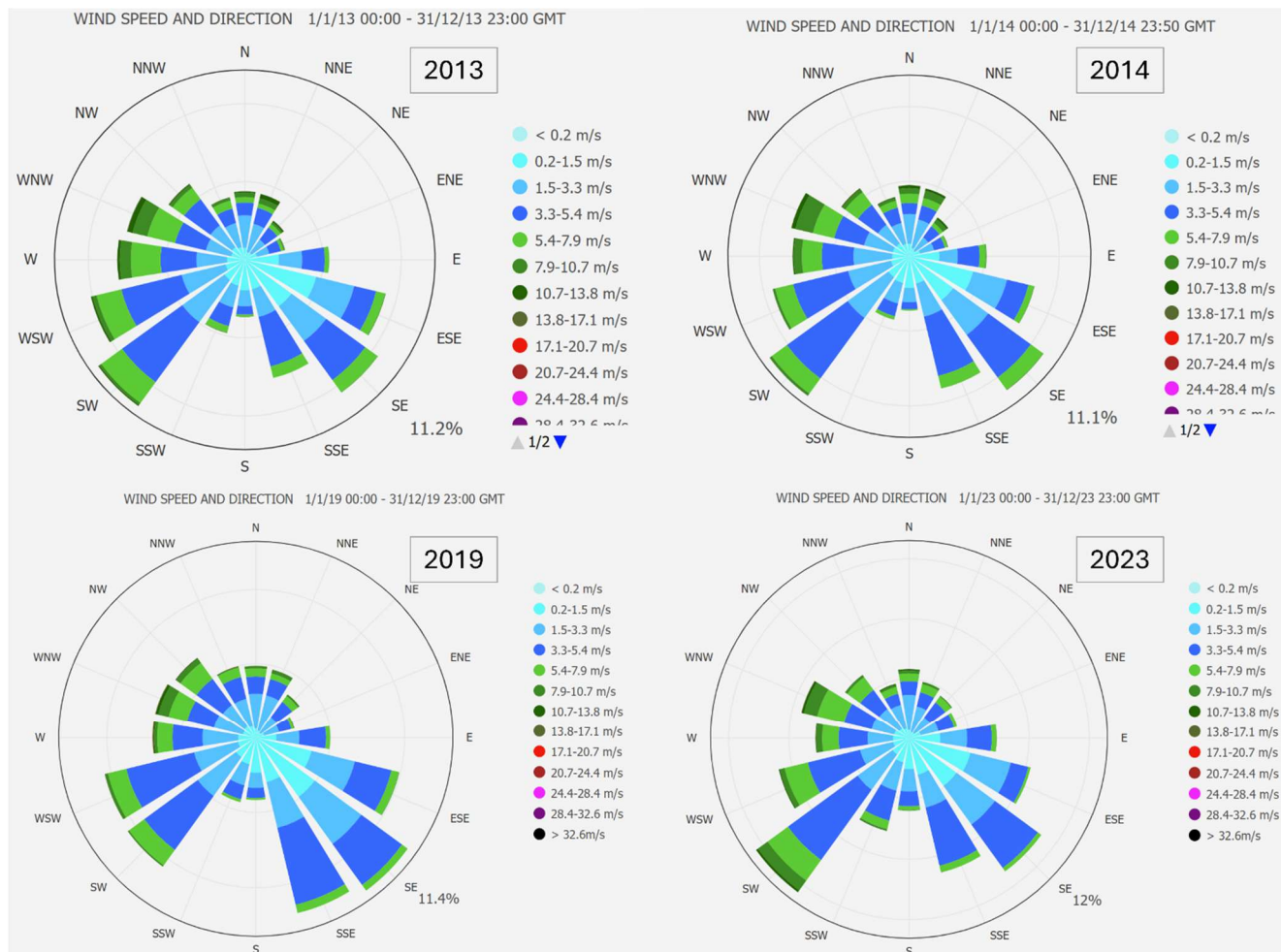


Figure 61. Annual average wind speed and direction in the Ancona region, for the years 2013, 2014, 2019, and 2023.

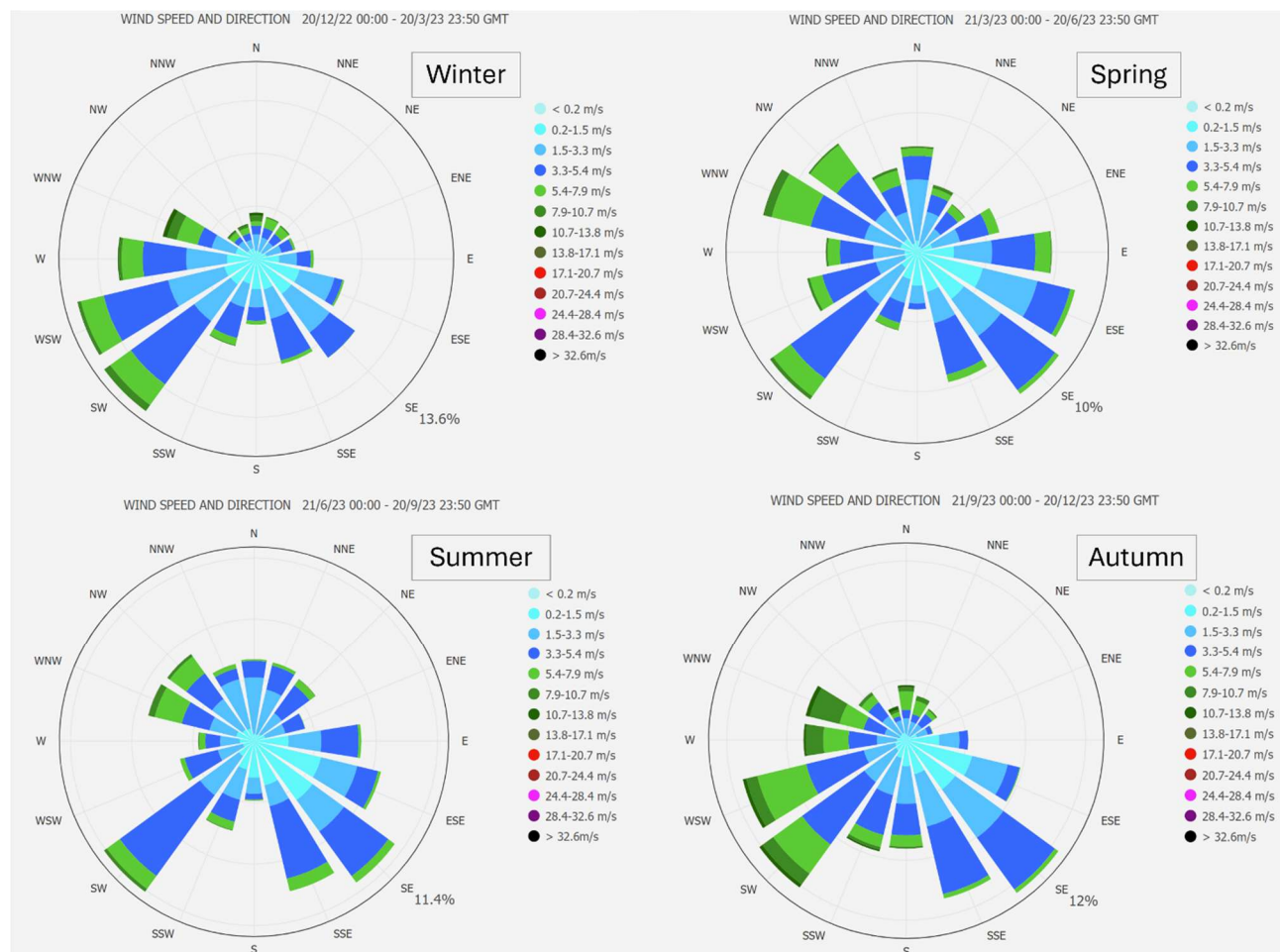


Figure 62. Average wind speed and direction in the Ancona region, for the Winter, Spring, Summer, and Autumn of 2023.

Wave height and direction analysis

Figure 63 presents the average wave height and direction, in the Ancona region, for the Winter, Spring, Summer, and Autumn of 2023. As observed, the wave direction in the region is relatively varied when the seasons are compared among themselves. In winter there is a predominance from North-Northeast (NNE), Northwest (NW), and, with a bit less frequency, Southeast (SE), being the NNE the direction with the highest waves. Spring provides a predominance of waves coming from the North (N), although the highest ones come from East (E) – Southeast (SE) directions. Summer comes with a calmer sea, i.e., a high percentage of waves are in the range < 0.5 meters height, with the majority of waves coming from NorthNorthwest (NNW) and South-Southeast (SSE) directions. Autumn comes with a highest predominance of waves from SE and heights up to 4 meters, although there is a secondary predominance of waves coming from West-Northwest (WNW).

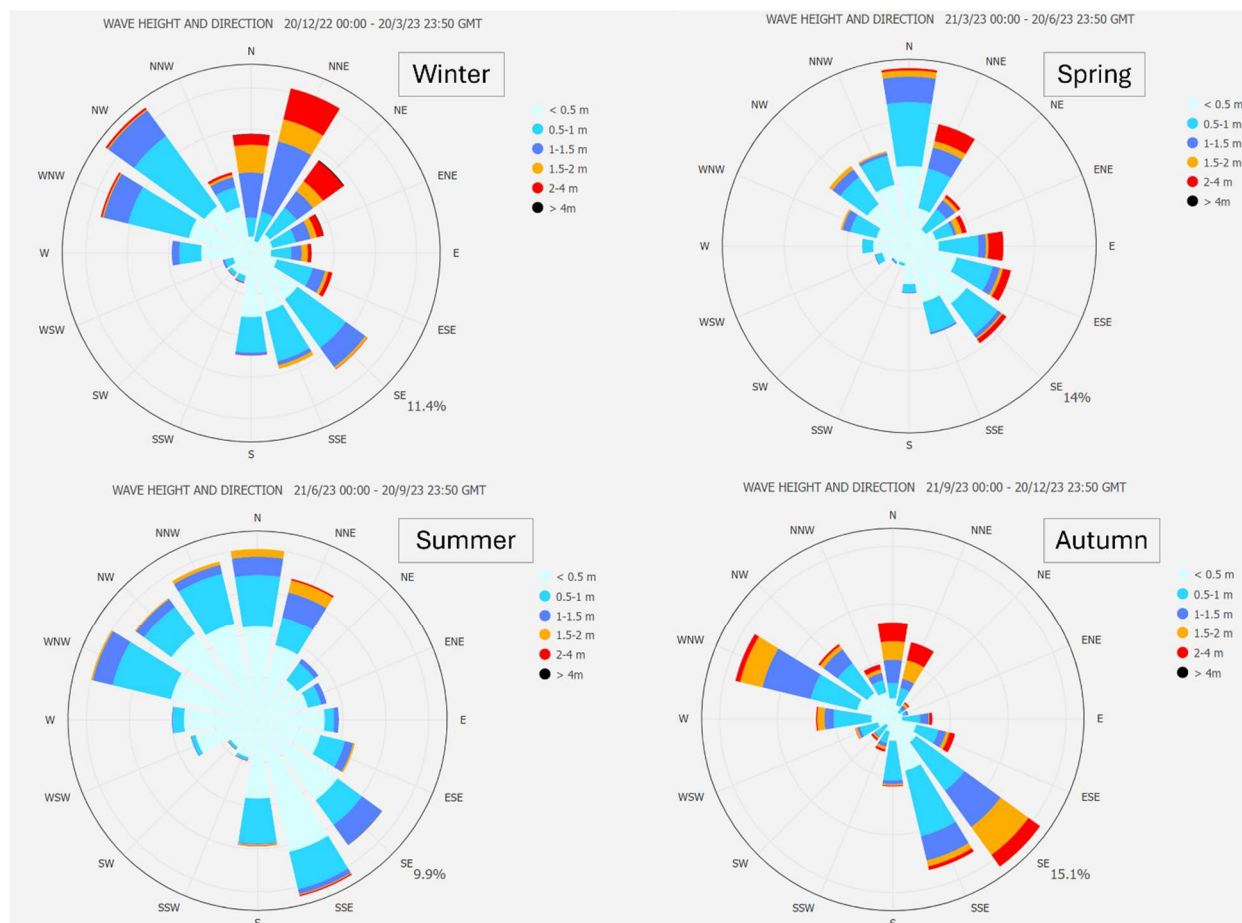


Figure 63. Average wave height and direction in the Ancona region, for the Winter, Spring, Summer, and Autumn of 2023.

Transportation analysis

As explained in the deliverable D.2.1.1, it is important to note that, for what concerns the cross-border route, it was defined that a hybrid installed technology would be a suitable solution, i.e., the trip from Ancona to Split would be operated by using the already existent diesel engines, whereas the hotelling phase would be powered by a proposed hydrogen technology solution. The reason is that the needed hydrogen storage to cover the whole trip for such a maritime route would be excessively large, which would compromise the feasibility and viability of a project with these characteristics.

Hotelling refers to the time spent by a ship when it is docked in a given port while its systems (such as lighting, heating, cooling, and communication) remain in operation. This energy demand is generally covered by auxiliary engines powered by HFO (Heavy Fuel Oil), MGO (Marine Gas Oil), or MDO (Marine Diesel Oil) as fuel, which results in significant local environmental pollution.

Italy – Croatia



TransH2

Table 19 introduces the main characteristics of the Marko Polo ferry operating in the Ancona – Split route.

Table 19: Characteristics of the Marko Polo ferry boat (Figure 39).

Main engine (MW)	Max speed (kn)	Length Overall (m)	Engine Type	Beam (m)	Draught (m)	Depth (m)	Deadweight (t)
15	23	128.1	4 X SWD 8TM410	19.6	6.2	7	1132

The hoteling operation is supported by the auxiliary engines. Due to the lack of data regarding specifically the Marko Polo vessel, it is possible to estimate the power of its auxiliary engines by referring to the scientific literature³². Then, it is possible to fix an average vessel ratio of auxiliary engine power over main

engine power equal to 0.18 and an engine load power of 40%. Table 20 reports the results of the case study, i.e., since the main engine power is 15 MW, the auxiliary.

Table 20: Estimation of auxiliary engine power and required hotelling energy.

Main engine (MW)	Auxiliary Engine (MW)	Required hotelling energy (MWh)
15	2.7	1.08

The characteristics of the Ancona–Split route are indicated in Table 21. Moreover, by analysing the ferry timetable, it is possible to estimate that the ferry's hoteling time is approximately 12 hours.

Table 21: Characteristics of the selected routes and ferries service speed.

Frequency (times/year)	Distance (NM)	Travel time (h)	Service speed (knots)
139	129	11.5	11

The Wärtsilä W6L32 marine engine with a power of 2.8 MW at 720 rpm is considered for the analysis. The datasheet provides a fuel consumption of 193 g/kWh at 50% of engine load, which can be a reasonable approximation for the evaluation of emissions. Based on the assumptions, the model estimates a fuel consumption of 2500 kg for 12 hours ferry hotelling. By considering an entire year

³² Trozzi, C. Emission estimate methodology for maritime navigation. U.S. Environmental Protection Agency. <https://www3.epa.gov/ttnchie1/conference/ei19/session10/trozzi.pdf>

of operation and based on the emission factors of Table 7, it is possible to calculate the Marko Polo ferry emissions for the hotelling phase (Figure 64) operating with auxiliary diesel engines.

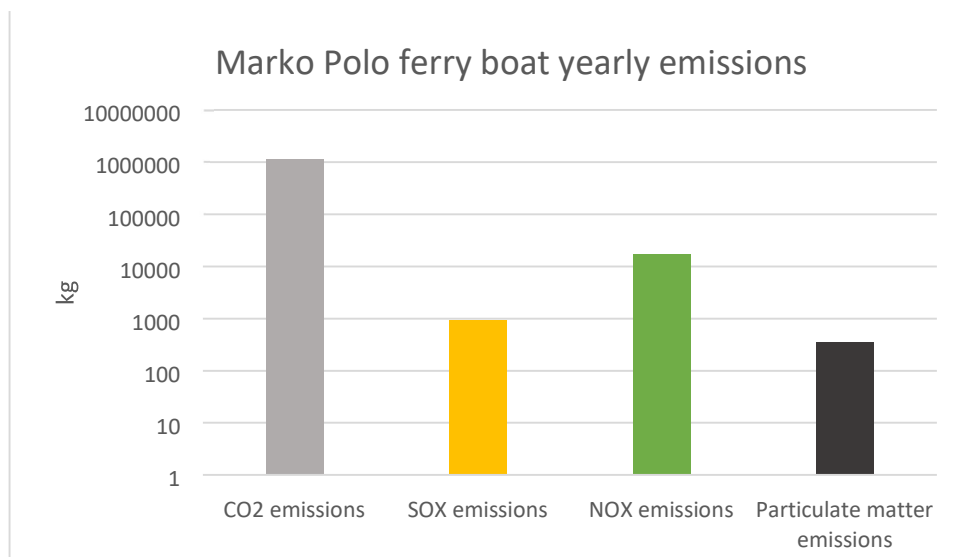


Figure 64. Marko Polo ferry boat yearly emissions for the hotelling phase.

For the estimation of hydrogen consumption during hotelling operations, the use of a hydrogen fuel cell system at berth (cold ironing) is considered. According to the Nedstack datasheet³³, a 100 kW fuel cell unit operates with an efficiency of 50%. Assuming the installation of 10 such units, the total hydrogen required to support ferry hotelling is approximately 60 kg per hour, resulting in a total consumption of around 720 kg over a 12-hour period. As a good approximation, it is possible to consider that the emissions presented through Figure 52 are the avoided emissions for a scenario where the hotelling phase of the Marko Polo ferry boat is fully powered by hydrogen.

Conclusions

The TransH2 deliverable D.2.1.3 focused on an in-depth analysis and transport models for the three selected maritime routes, as indicated in the deliverable D.2.1.2. By aiming at enhancing the sustainability of sea-mobility in the Adriatic Sea region, the mentioned in-depth analysis was developed from the environmental, navigational, and transport model perspectives. The environmental analysis considered air quality and Natura 2000 sites. The navigational analysis was based on the route characteristics, as well as meteorological and oceanographic analysis. Finally, the transport models were based on the calculation of fuel consumption (both for the conventional scenario with diesel engines and for a new scenario with hydrogen powered technologies) and the resultant emissions.

³³ <https://nedstack.com/sites/default/files/2024-12/pemgen-mobile-241202-draft.pdf>

Italy – Croatia



TransH2

In accordance with the outcomes from the online workshop and the following applied survey (which are detailed in the deliverable D.2.1.2), the TransH2 project partners were able to identify the three use-cases (maritime routes) that would be the targets for further investigation for transition towards hydrogen powered technology, based on the interest of key stakeholders. The three selected use-cases are: Tronchetto-Lido (regional Italian route), Split-Supetar (regional Croatian route), and Ancona-Split (international cross-border route). Next, the reader can find some specific conclusions for each selected maritime route.

Tronchetto-Lido route:

- The conducted environmental analysis demonstrated that, from the air quality perspective, all the analysed parameters (SO₂, NO₂, CO, PM_{2.5}, and PM₁₀) are in agreement with local regulations (according to a report issued in 2023 by the local authority), although measures should be taken in order to maintain such scenario. For what concerns the Natura 2000 sites, the analysis showed that Tronchetto-Lido route crosses an area designated under the Birds Directive and, for that reason, the transition to hydrogen technologies would results in emission reduction which will be beneficial for that area.
- Three main conclusions can be drawn from the navigational analysis: (i) the water depth along the route is particularly shallow, in the range between 5 and 15 meters, (ii) the wind direction has a predominance from the Northeast direction, with a speed range from 1 to 14 m/s, and (iii) the waves direction has a predominance between the East-Northeast and Southeast directions, with heights in the range between 1 to 4 meters.
- For the Italian regional route, the transport model revealed, for the conventional scenario, a consumption of 32 kg of diesel per trip, with a consequent amount of CO₂ emission in the order of 17 tons per week. On the other hand, and under the same conditions, the model also revealed a hydrogen consumption of 7 kg per trip, with a CO₂ emission avoidance level equal to the emission resulted from the conventional scenario (17 tons per week).

Split-Supetar route:

- The air quality parameters (SO₂, NO₂, CO, PM_{2.5}, and PM₁₀) in the Split region demonstrated an overall compliance with local regulations, although NO₂, PM_{2.5}, and PM₁₀ require close monitoring, as their daily average concentrations have been very close to the regulated thresholds. For what concerns the Natura 2000 sites, the analysis concluded that the route does not affect any designated site directly, since the vessel's trajectory does not cross any protected area (although the nearby sites could be benefited from a possible emission reduction).
- Main conclusions about the navigational analysis: (i) the water depth along the route is in the range between 10 and 50 meters, (ii) the wind direction has a predominance from the Northeast direction, with speed ranges that could be over 5.4 m/s, and (iii) the wave heights did not exceed 1.5 meters in the analysed year.

Italy – Croatia



TransH2

- For the Croatian regional route, the transport model resulted, for the conventional scenario, in a consumption of 274 kg of diesel per trip, with a consequent amount of CO₂ emission in the order between 53 to 83 tons per week (depending on the season of the year). On the other hand, and under the same conditions, the model also revealed a hydrogen consumption of 74 kg per trip, with a CO₂ emission avoidance level equal to the emission resulted from the conventional scenario (between 53 to 83 tons per week).

Ancona-Split route

- The same air quality parameters have been analysed for this route. According to the collected data, the Ancona region also demonstrated an overall compliance with local regulations for all parameters, but PM_{2.5}, and PM₁₀. The data shows that the winter and summer seasons are critical periods for these two air quality parameters. For that reason, they require close monitoring and possible mitigation measures. For what concerns the Natura 2000 sites, the analysis concluded that the route does not affect any designated site directly, since the vessel's trajectory does not cross any protected area (although the nearby sites could be benefited from a possible emission reduction).
- The navigational analysis concluded that: (i) this route has a much wider range of water depth (10 to 400 meters) since it crosses the Adriatic Sea, (ii) the wind direction predominance varies between Southeast, South, and Southwest, under speed ranging from 0.2 to 14 m/s, and (iii) the pattern of wave direction and heights undergo important changes throughout the year.
- For the cross-border route, the transport model revealed, for the conventional scenario, a consumption of 2500 kg of diesel for 12 hours of hotelling operation, with a consequent amount of CO₂ emission in the order of 1100 tons per year. On the other hand, and under the same conditions, the model also revealed a hydrogen consumption of 720 kg for 12 hours of hotelling operation, with a CO₂ emission avoidance level equal to the emission resulted from the conventional scenario (1100 tons per year).

The data regarding the routes and the technical configuration of the vessels will be revised and further detailed in the deliverable D.2.1.4 in order to analyse different technical options for the regional and the international routes.

10. Business Model of Cooperation

The business model of cooperation developed within the TransH2 project is founded on the recognition that the transition towards hydrogen-fuelled maritime transport represents a **systemic transformation** rather than a single technological upgrade. The successful deployment of hydrogen solutions in cross-border maritime mobility requires coordinated action across the entire value chain, encompassing energy production, port infrastructure, vessel design and operation, regulatory frameworks, and market uptake. Consequently, the cooperation model is structured as a **multi-level, cross-border governance and collaboration framework**, rather than a traditional linear business model.

At the strategic level, the cooperation model is anchored in **cross-border alignment of public authorities, regional administrations, and policy-making bodies**. These actors provide the enabling environment through strategic planning, regulatory harmonisation, and long-term vision-setting aligned with European decarbonisation objectives. Their role is essential in reducing fragmentation between national systems, ensuring consistency of safety and environmental standards, and creating predictable conditions for investment and innovation in hydrogen-based maritime transport.

At the operational level, the model brings together **ports, transport operators, technology providers, research institutions, and business-support organisations** into a structured cooperation ecosystem. Ports play a central role as system integrators, acting as physical and organisational hubs where hydrogen production or delivery, storage, bunkering infrastructure, and vessel operations converge. Transport operators contribute operational knowledge, demand forecasting, and real-life testing of hydrogen-powered vessels on cross-border and regional routes. Research institutions and technical partners support the cooperation model through feasibility analyses, technology assessment, safety studies, and performance evaluation, ensuring that solutions are evidence-based and transferable.

The cooperation model is intentionally designed as **open and modular**, allowing for gradual expansion in terms of both geography and stakeholder participation. New ports, operators, and energy suppliers can be integrated into the cooperation framework without the need for structural redesign. This modularity is a prerequisite for replication in additional Adriatic locations and for future scaling at national or macro-regional level. Cooperation is formalised through agreements such as memoranda of understanding, partnership agreements, and joint working arrangements, which define roles, responsibilities, and decision-making processes while preserving flexibility for local adaptation.

A key feature of the TransH2 cooperation model is its **phased approach to implementation**. In the initial phase, cooperation focuses on knowledge generation, joint planning, pilot studies, and capacity building. During this phase, emphasis is placed on trust-building, alignment of expectations, and

Italy – Croatia



TransH2

development of shared technical and operational standards. In the intermediate phase, cooperation evolves towards pilot implementation and demonstration activities, including limited-scale hydrogen bunkering and vessel operation. In the long-term phase, the cooperation model supports transition to regular operations and broader market uptake, with increasing involvement of commercial actors and reduced dependence on project-based collaboration.

The model explicitly acknowledges that hydrogen maritime transport is currently characterised by **high uncertainty and technological immaturity**. Therefore, cooperation is structured to enable collective risk management and learning. Risks related to technology performance, regulatory approval, safety compliance, and market acceptance are addressed jointly rather than by individual actors. This collective approach lowers entry barriers, particularly for smaller ports and regional operators, and accelerates the diffusion of innovation across the cross-border area.

Finally, the business model of cooperation embeds **continuous knowledge exchange and institutional learning** as core components. Training activities, joint workshops, shared data platforms, and dissemination of lessons learned ensure that experience gained in pilot locations contributes directly to replication and policy development. In this way, cooperation within TransH2 extends beyond the project lifetime and establishes a durable foundation for long-term cross-border collaboration on zero-emission maritime mobility.

11. Financial Construction

The financial construction accompanying the TransH2 cooperation model reflects the specific characteristics of hydrogen-based maritime transport, namely **high upfront investment requirements, long payback periods, and elevated technological and market risks**. As a result, the financial framework is designed to support progressive deployment through a combination of public funding, shared financial responsibility, and gradual integration of private capital, rather than immediate reliance on market-driven financing.

In the early phase of development, financial resources are primarily directed towards **non-revenue-generating activities**, such as research, feasibility studies, conceptual and technical design, safety assessments, regulatory analysis, and capacity building. These activities are predominantly financed through public funding instruments, including Interreg programme support and national or regional public contributions. This approach is justified by the public-good nature of these activities, their role in reducing systemic uncertainty, and their contribution to long-term climate and transport policy objectives.

As the cooperation progresses towards pilot implementation, the financial construction expands to include **capital expenditures related to demonstration infrastructure and vessels**. These investments typically involve hydrogen storage systems, bunkering equipment, port-side adaptations, and pilot-scale hydrogen production or supply arrangements. At this stage, the financial model continues to rely significantly on public funding and state-aid-compliant support mechanisms, while encouraging co-financing by participating organisations. Public funding serves to de-risk early investments and create reference cases that can be used to attract future financing.

Operational expenditures associated with pilot activities—such as hydrogen procurement, system maintenance, training, and operational monitoring—are treated as part of the learning process rather than fully commercial costs. The financial construction recognises that, under current market conditions, hydrogen-based maritime operations are unlikely to be cost-competitive with conventional fuels without supportive policy instruments. Therefore, pilot operations are financially structured to prioritise learning outcomes, data collection, and validation of operational models over short-term profitability.

In the medium to long term, the financial construction envisages a **gradual shift towards hybrid financing models**, combining public support with increasing private sector participation. This may include public-private partnerships, long-term service contracts, concession arrangements for bunkering infrastructure, or joint investment vehicles involving ports, energy providers, and transport operators. The timing and structure of such arrangements depend on technological maturity, regulatory clarity, and the availability of stable demand for hydrogen fuel.

Risk-sharing mechanisms are an integral element of the financial construction. These include contractual allocation of risks between infrastructure providers and vessel operators, long-term

Italy – Croatia



TransH2

hydrogen supply agreements to stabilise fuel prices, and coordinated investment planning to avoid stranded assets. By distributing risks across multiple actors and governance levels, the financial model enhances bankability and reduces the likelihood of investment lock-in or premature failure.

The financial construction also takes into account **external economic drivers**, such as carbon pricing, fuel taxation, emission regulations, and potential incentives for zero-emission transport. Over time, these factors are expected to improve the relative cost position of hydrogen compared to fossil fuels, thereby reducing the need for direct public subsidies. Economies of scale, technological learning effects, and declining costs of renewable electricity and electrolyzers are likewise expected to contribute to improved financial viability.

In conclusion, the financial construction developed within TransH2 is intentionally **adaptive and long-term oriented**. It supports early-stage innovation through public investment, enables gradual transition towards operational deployment through blended financing, and prepares the ground for future commercialisation once market and regulatory conditions allow. This approach ensures financial realism while maintaining alignment with European decarbonisation objectives and the strategic goals of cross-border maritime cooperation.

12. Investment and economic feasibility

This Chapter provides site-specific investment strategies for the three TransH2 pilot cases, applying the general financing frameworks documented in Chapter 4 to the particular contexts of Trieste, Split, and Zadar. While Chapter 4 described available funding instruments and their operational mechanisms (Innovation Fund, AFIF, IPCEI, national programmes, private finance vehicles), this chapter addresses how to combine these instruments strategically based on each location's documented supply chain positioning, institutional readiness, and project-specific requirements established in Chapter 3.

The investment strategies presented here combine established facts from preceding analysis with reasoned deductions and strategic hypotheses. Where this chapter proposes specific financing allocations or approaches, these should be understood as indicative frameworks requiring validation through actual funding call outcomes, stakeholder negotiations, and market conditions at time of implementation

12.1 Overview on funding and investment mix in Italy

The financing strategy for Trieste is informed by several documented: proximity to hydrogen production facilities (Monfalcone at approximately 35 km, Hydrogen Hub Trieste in port area, both operational 2025-2026 per Section 3.3.4), existence of PNRR-funded hydrogen infrastructure (€15.8M Hydrogen Hub Trieste allocation per Section 4.3.1), TEN-T core network status (Ch. 3.3), and availability of regional funding mechanisms (Friuli Venezia Giulia allocations documented in Ch. 4.3.1). Based on the cost analysis in Ch. 3.3, Trieste's delivered hydrogen cost is estimated at €7-9/kg compared to €9-13/kg for supply-constrained scenarios, suggesting a structural OPEX advantage of approximately €0.7M-€1.4M annually at reference throughput (360 000 kg/year). This cost positioning, combined with institutional capacity demonstrated through active PNRR implementation, provides a foundation for constructing a financing strategy that leverages both EU and national instruments while attracting private capital through improved project economics.

12.1.1 EU funding & grants (non-dilutive support)

12.1.1.1 Innovation Fund (Hydrogen Auction Premiums)

Use the Innovation Fund hydrogen auction mechanism to secure output-based premiums (€/kg H₂ produced/bunkered) over up to 10 years. This directly supports revenue and improves bankability

Italy – Croatia



TransH2

for early operations. While specific winners are finalized case-by-case, Italy has been active and Innovation Fund continues to invest heavily in hydrogen technologies across Europe.

The mechanism is detailed in Ch. 4.2.1; for Trieste, the delivered hydrogen costs (€7-9/kg as estimated in Section 3.3.2) suggest that competitive bid pricing may be achievable, though actual auction outcomes depend on competing project economics and available budget at time of call. The premium may bridge the gap between levelized cost of hydrogen and market price, with revenue support potentially equivalent to 20-30% of project IRR contribution based on typical auction outcomes documented in Ch. 4.2.1.

12.1.1.2 Alternative Fuels Infrastructure Facility (AFIF) — CEF Transport

Apply for AFIF funding under the Alternative Fuels Infrastructure Facility to support the construction of alternative fuels infrastructure (including hydrogen refuelling stations and related bunkering), ideally in combination with private finance for blended capital. The AFIF budget is significant and still open for proposals with cut-off dates (e.g., 11 June 2025 and future rounds). As documented in Ch. 4.2.2, AFIF provides grants covering 30-50% of eligible CAPEX, with higher co-financing rates potentially available for projects demonstrating strategic TEN-T alignment or multimodal integration. Use AFIF to co-finance CAPEX up to 50% (or more where relevant), blended with private debt/equity and complement AFIF with Innovation Fund premium for revenue support.

TEN-T / CEF Synergies

Trieste as a key Trans-European Transport Network (TEN-T) node qualifies strategically for connecting hydrogen infrastructure with multimodal freight and maritime corridors; projects aligned with CEF climate transition goals are more competitive.

12.1.2 National funding (Italy)

12.1.2.1 PNRR (National Recovery and Resilience Plan)

Trieste already benefits from a Hydrogen Hub project funded through PNRR (€15.8M) plus Horizon Europe contributions, including electrolysis and PV capacity, demonstrating Italy's commitment to regional hydrogen value chains.

- A hydrogen refuelling station (HRS) can integrate with the existing PNRR-enabled hub, shortening time to operations, and may be part of a broader hydrogen corridor initiative.

Italy – Croatia



TransH2

12.1.2.2 National grants / incentives for clean fuels

- Italy's Ministry of Infrastructure and Transport may support alternative fuel stations under broader transport decarbonisation calls (e.g., AFIR-aligned investments).
- Complementary national funds may be available for energy transition infrastructure and industrial decarbonisation.

3. Regional funding (Friuli Venezia Giulia)

12.1.2.3 Regional grants & innovation programs

The Friuli Venezia Giulia region has allocated millions in regional funds to hydrogen research infrastructure and pilot projects (e.g., €2M E4H2 labs, €1.08M for IMPACT-H2 and allied projects). These demonstrate a regional focus on developing hydrogen ecosystem capabilities that can underpin infrastructure deployment.

More recently, as documented in Chapter 4, FVG allocated approximately €15M for flagship renewable hydrogen production projects in brownfield areas (2025) and €10M for research infrastructures (2024). While the flagship production call targets large-scale electrolyser installations, there is no explicit exclusion of infrastructure projects that enable utilization of regionally-funded production capacity. Stakeholders should consider engaging Regione FVG authorities to explore whether HRS deployment could qualify for flagship project funding as enabling infrastructure, or whether future regional calls might specifically target hydrogen distribution and refuelling infrastructure.

12.1.2.4 Interregional & Cross-Border Platforms

- North Adriatic Hydrogen Valley investments and transnational partnerships (e.g., €7.6M for clean hydrogen projects) can support collaborative innovation and may unlock I3 EU calls involving consortiums across regions and states.

The NACHIP (North Adriatic Clean Hydrogen Investment Platform) project, mentioned in Chapter 4, provides €7.6M ERDF funding for cascade financing to SMEs and innovation projects at TRL 6-9. While NACHIP is innovation-focused rather than infrastructure-focused, it could provide complementary funding for specific HRS components such as advanced monitoring systems, safety innovations, or SME integration within the hydrogen supply chain. The transnational dimension (Croatia-Slovenia-

Italy – Croatia



TransH2

Italy cooperation) also creates potential for Interreg or other cross-border funding mechanisms if the Trieste HRS is positioned as a node within broader Adriatic hydrogen corridor development.

Public-Private Partnerships (PPPs)

Port Authority + Private Developer Concession

Structure the HRS as a concession with the Port Authority of Trieste, where: the port authority contributes land, permitting support, infrastructure interfaces, and facilitation of maritime customers, while the private partner provides equity and operational expertise (often via special purpose vehicle).

This allocation of responsibilities is consistent with PPP structures described in Section 4.4.1, where public entities typically provide land and regulatory coordination while private operators assume technology and operational performance risk. For Trieste, the Port Authority (AdSP) could contribute land concession within the port area, coordinate permitting processes with fire services and maritime authorities, and potentially aggregate demand through commitment to convert port-owned vessel fleet (tugs, pilot boats, service vessels) to hydrogen, providing baseline utilization guarantees that de-risk private investment. The private partner, potentially an energy company (such as Hydrogen Hub Trieste operators AcegasApsAmga, or strategic investors like Snam or Edison), a maritime operator, or a specialized hydrogen infrastructure developer, would provide equity capital, procure HRS equipment, manage construction, and operate the facility under a long-term concession agreement.

12.1.2.5 Risk Sharing & Availability Payments

PPP may include availability payments or minimum revenue guarantees from the public side tied to service availability, further de-risking debt service.

Such mechanisms are particularly relevant in early-stage hydrogen markets where utilization ramp-up creates cash flow uncertainty. If the Port Authority or regional/national entities provide availability payments (fixed payments conditional on HRS operational availability regardless of throughput volume) or minimum revenue guarantees (compensation if hydrogen sales fall below agreed thresholds), this transfers demand risk from private operator to public sector, improving bankability for debt providers and reducing required equity returns. However, these commitments would create fiscal obligations for public partners that must be balanced against policy benefits of accelerated infrastructure deployment.

12.1.2.6 Integration into Broader Infrastructure Projects

The HRS rollout into broader multimodal energy transition investments (shore power, electrification services), making the PPP more attractive and complex.

Co-location with shore power infrastructure, for example, may allow shared electrical grid connection, transformer capacity, and potentially civil works, reducing incremental HRS infrastructure costs. Integration with port electrification strategy (electric cranes, charging infrastructure for port equipment and trucks) could create economies of scope in planning, permitting, and operations. This bundled approach may be more attractive to private infrastructure investors seeking larger-scale, diversified port energy transition portfolios, and could facilitate green bond issuance (discussed in Ch. 5.1.5) at viable scale.

12.1.3 Green / Blue Bonds & Thematic Capital Markets Instruments

12.1.3.1 Green Bonds

This instrument could be activated through the Port Authority (sub-sovereign issuer), or a special purpose joint venture with private sponsor and institutional partner. Use proceeds to fund the CAPEX of hydrogen bunkering infrastructure, aligned with the EU Taxonomy's clean fuels and transport infrastructure categories.

As discussed in Ch. 4.2.4, hydrogen bunkering infrastructure qualifies under EU Taxonomy criteria, enabling green bond certification under EU Green Bond Standard or Climate Bonds Initiative frameworks. For Trieste, the Port Authority could issue a green bond backed by port revenues and dedicated to hydrogen infrastructure, with tenor of 15-20 years matched to infrastructure lifetime. However, minimum viable issuance scale for bond markets is typically €10M-€20M+, which exceeds the estimated €7M CAPEX for a single HRS (as per Ch. 3.3.3). Therefore, green bond financing would likely require bundling HRS investment with other port green infrastructure (shore power, electrification, renewable energy installations) to achieve sufficient scale. Alternatively, a special purpose vehicle combining public and private sponsors could issue project bonds backed by HRS cash flows and public revenue support (Innovation Fund premiums, availability payments), though this structure is less common for early-stage hydrogen infrastructure given execution and credit rating challenges.

Italy – Croatia



TransH2

12.1.3.2 Blue Bonds

Leverage port's maritime decarbonisation and coastal ecosystem benefits to attract blue bond investors by highlighting maritime emission reductions, cleaner air quality in coastal zones and alignment with Sustainable Blue Economy objectives.

Green/blue bonds can attract pension funds and ESG-oriented capital, reducing WACC and extending tenor beyond what typical project finance alone can achieve.

Blue bonds, as an emerging subset of green bonds focused on ocean and coastal sustainability, could be particularly relevant for port-based hydrogen infrastructure given the maritime decarbonization narrative. Potential investors include specialized blue economy funds or institutional investors with ocean sustainability mandates. The blue bond framing emphasizes not only climate benefits but also air quality improvements in port and urban coastal areas (reduction of NO_x, SO_x, particulate matter from shipping), marine ecosystem protection through zero-emission shipping corridors, and sustainable blue economy development aligned with EU Blue Economy objectives. However, the blue bond market remains smaller and less mature than the broader green bond market, and certification frameworks are still evolving, which may limit immediate applicability pending market development.

12.1.4 Commercial Debt & Institutional Investors

12.1.4.1 Senior Project Finance Debt

Secure long-term loans (up to 15–20 years) from commercial banks and/or the European Investment Bank (EIB) or national promotional banks — possibly with public guarantees or partial credit enhancements.

For Trieste, potential debt providers include EIB (which has mandate for climate infrastructure and TEN-T projects), CDP (Cassa Depositi e Prestiti, Italian promotional bank with favorable pricing for strategic infrastructure), and commercial banks with project finance capabilities. Debt structuring would typically target loan-to-value ratios of 60–70% of total CAPEX, with tenor of 15 years matched to operational cash flow profile. Given the estimated CAPEX of €7.0M for reference HRS capacity (Ch. 3.3.3), and assuming grant coverage of 60–70% (€4.2M–€4.9M from AFIF, PNRR, and regional sources), the remaining €2.1M–€2.8M could be financed through a combination of debt (€1.1M–€1.5M) and equity (€0.7M–€1.0M). Bankability depends on operational cash flow projections, which in turn depend critically on Innovation Fund revenue support (as hydrogen sales revenue alone at uncertain market prices may be insufficient for debt service in early operational years) and ferry operator

Italy – Croatia



TransH2

offtake commitments providing volume certainty. Credit enhancement through public guarantees (SACE, Italian export credit agency, or InvestEU instruments) could improve pricing and enable higher leverage, but would require specific negotiation with guarantee providers.

12.1.4.2 Institutional Equity / Co-Investment Funds

Attract equity from energy transition funds, hydrogen tech funds (such as emerging European hydrogen tech investment funds), or strategic partners in energy/maritime sectors. Potential equity investors described in Ch. 4.4.2 include Hy24 Clean Hydrogen Infrastructure Fund (~€2B raised, hydrogen-dedicated), Copenhagen Infrastructure Partners' CI Energy Transition Fund I (€3B), and Italian strategic investors such as Snam (pursuing hydrogen infrastructure investments), Edison (renewable energy focus), or CDP Equity (strategic industrial investments arm of Cassa di Risparmio di Trieste). Maritime sector strategic investors could include shipping lines with decarbonization commitments or port operators with hydrogen infrastructure experience. Target equity returns for early-stage hydrogen infrastructure typically range 8-12% IRR on a risk-adjusted basis. Whether Trieste can deliver these returns depends on operational cash flows (hydrogen sales plus Innovation Fund premium) relative to OPEX (including hydrogen procurement at €7-9/kg estimated cost per Section 3.3.2), capacity utilization ramp-up, and grant leverage reducing equity exposure. The documented supply chain advantage (lower delivered hydrogen costs vs. supply-constrained scenarios) improves cash flow margins and should enhance attractiveness to equity investors, though independent due diligence on market demand (ferry operator conversion commitments) and operational assumptions would be required.

Table 2 shows an indicative financing structure combining the documented funding instrument parameters from Ch. 4 with Trieste-specific strategic context established in Ch. 3.3 and 5.1. The allocations represent typical share ranges observed in comparable hydrogen infrastructure projects and should be understood as targets subject to refinement based on actual call outcomes, competitive evaluation results, stakeholder negotiations, and market conditions at time of financial close. The Innovation Fund premium is expressed as IRR contribution rather than CAPEX percentage because it provides revenue support over the operational period rather than upfront capital. Actual financing outcomes will depend on successful navigation of competitive funding processes (AFIF, Innovation Fund auctions), confirmation of PNRR/regional funding eligibility, formalization of PPP governance structures, and private investor due diligence on project economics and risk allocation

Source	Role	Typical Share
Innovation Fund Premium (€/kg)	Revenue support bridging gap	20–30% of IRR support

Italy – Croatia



AFIF (CEF Transport)	CAPEX Co-financing	30–50% of eligible CAPEX
PNRR / National Grants	Strategic build-out	15–25%
Regional FVG Funds	Innovation, R&D complement	5–10%
Port Authority PPP Equity	Equity anchor	10–20%
Green/Blue Bonds	Medium/long debt, low cost	30–50%
Commercial/Promotional Bank Debt	Project finance	30–40%

Table 2 - Example Optimal Mix (Indicative) to be reviewed

12.2 Overview on funding and investment mix in Croatia

The financing strategy for Croatian pilot cases is based on the supply chain and institutional characteristics described in Ch. 3.4, 3.5, and 4.3.2. Both Split and Zadar face the constraint of no confirmed local hydrogen production, with potential supply distances of 150-400+ km from Zagreb region, cross-border suppliers, or future coastal facilities (Ch 3.4.4, 3.5.4), resulting in estimated delivered hydrogen costs of €9-13/kg for Split and €8.5-13.5/kg for Zadar compared to €7-9/kg for Trieste. This cost differential of approximately €2-4/kg translates to roughly €0.7M-€1.4M/year higher OPEX at reference throughput (360,000 kg/year), which materially impacts project economics and necessitates higher public co-financing to compensate for elevated operational risk. Croatia's hydrogen market is nascent, with the National Hydrogen Programme allocating ~€29.6M for HRS deployment (Ch. 4.3.2) and precedents like the INA Rijeka project (€45.5M total, €15M RRP grant) demonstrating emerging institutional capacity but limited operational experience with maritime hydrogen infrastructure. These factors suggest that Croatian cases require financing structures with higher grant shares (60-70% or above for demonstration-focused approaches) and a strong fund revenue support to bridge the cost gap and attract private capital. The analysis below examines how to combine Croatian national programmes, EU instruments, and private finance to address these constraints while managing investment risk through phased deployment where appropriate.

12.2.1 National Support for Hydrogen Refuelling Stations (HRS)

12.2.1.1 Croatian Ministry Funding Programme

Croatia has launched a dedicated subsidy programme targeted at constructing hydrogen refuelling stations for vehicles (cars, buses, trucks) as part of accelerating decarbonisation of transport, including hydrogen uptake in mobility infrastructure. The programme allocates a total of about €29.6 million, of which approx €23 million is earmarked for hydrogen refuelling infrastructure deployment over the next few years, with around 65 % of funding expected to be rolled out in the first year.

Italy – Croatia



TransH2

It aims to install at least six hydrogen stations by 2026 on key transport corridors, potentially expandable depending on project proposals and planning.

This call is managed at the national level via the Ministry of Economy and Sustainable Development and could be leveraged for a Split or Zadar HRS if that location aligns with Croatia's broader alternative fuels deployment strategy.

As mentioned in Ch. 4.3.2, the programme currently targets road transport applications with per-station support ceilings of up to approximately €2M for passenger vehicle stations and up to €3.5M for bus/heavy-duty applications. Maritime HRS are not explicitly included in the programme scope as currently defined, which creates an eligibility uncertainty that requires resolution through proactive stakeholder engagement with the Ministry of Economy and Ministry of Sea, Transport and Infrastructure. Given that Split and Zadar are TEN-T comprehensive network nodes with significant maritime transport functions (Ch. 3.4.1, 3.5.1), there is a reasonable basis for advocating that port-based HRS serving ferry operations should be accommodated within the programme's TEN-T corridor deployment logic. If maritime HRS eligibility is confirmed, it would be reasonable to target the upper end of documented support ranges (€2.5M-€3.5M per station) given higher technical complexity and larger daily capacity requirements compared to road HRS. For a €7.0M CAPEX station, this would represent 36-50% public co-financing from the national programme alone, providing a substantial anchor for overall financing structure. However, absent ministerial confirmation of eligibility, this funding source remains contingent and alternative scenarios must be maintained

12.2.1.2 EU Funds & CEF/AFIF (Alternative Fuels Infrastructure Facility)

12.2.1.2.1 AFIF / CEF Transport for Split and Zadar HRS or Bunkering

The Alternative Fuels Infrastructure Facility (AFIF), under the Connecting Europe Facility (CEF) – Transport programme, finances infrastructure rollouts for alternative fuels including hydrogen refuelling and, importantly, supply to ports and maritime applications. This means projects at or near the Port of Zadar could qualify, especially if integrated with broader TEN-T network goals or linked multimodal transport infrastructure. As detailed in Ch. 4.2.2, AFIF operates through rolling calls with co-financing rates typically in the range of 30-50% of eligible CAPEX, with potential for higher rates for cohesion country projects (Croatia qualifies) or demonstration/lighthouse initiatives. The total AFIF budget for 2024-2025 was approximately €1B, with 208 projects funded since 2021 representing €1.3B in EU contributions.

Italy – Croatia



TransH2

Infrastructure may include hydrogen refuelling stations for vehicles and vessels, plus relevant supply systems at port locations. Eligible projects must be mature and often supported by implementing partners or financial institutions (e.g., EIB, national promotional banks). Infrastructure may include hydrogen refuelling stations for vehicles and vessels, plus relevant supply systems at port locations. Eligible projects must be mature and often supported by implementing partners or financial institutions (e.g., EIB, national promotional banks)

AFIF is ideal for CAPEX co-financing, helping reduce upfront investment costs when blended with national or regional co-financing and private capital. For Croatian maritime HRS, application strategy should emphasize lighthouse/demonstration value (first Croatian maritime hydrogen infrastructure, knowledge creation for broader Adriatic replication), cohesion country status, TEN-T alignment, and island connectivity social/environmental benefits. A coordinated approach presenting Split and Zadar as an integrated Croatian maritime hydrogen corridor demonstration could strengthen competitiveness relative to standalone applications. Based on documented AFIF parameters and strategic positioning, it is reasonable to target co-financing at 40-50% of eligible CAPEX (€2.8M-€3.5M for €7.0M project), though actual outcomes depend on competitive evaluation against other European projects and available budget at call cut-off dates. Technical assistance from EIB via JASPERS (Joint Assistance to Support Projects in European Regions) programme could support application preparation and improve quality, particularly given nascent institutional experience with hydrogen project development in Croatian context.

12.2.1.2.2 EU Innovation Fund (Revenue Support)

Although not Croatia-specific, the EU Innovation Fund offers output-based support (e.g., premiums per kg of hydrogen produced/sold) for advanced clean hydrogen projects in Member States. This could support a hydrogen production + refuelling hub concept in Split or Zadar by bridging revenue gaps, especially for green hydrogen supply that ties into broader maritime and mobility decarbonisation.

This aligns with EU climate and industrial policy priorities and supports commercial sustainability through revenue incentives.

As documented in Ch. 4.2.1, the Innovation Fund operates through competitive auctions where projects bid a fixed premium per kg of hydrogen that bridges the gap between levelized cost and expected market price. For Croatian cases, given the elevated delivered hydrogen costs documented in Sections 3.4.2 and 3.5.2 (€9-13/kg range), the premium required to achieve commercial viability

Italy – Croatia



TransH2

would be in the range of €3-9/kg depending on market price assumptions (€4-6/kg market price based on FuelEU Maritime compliance economics, though this is uncertain). This represents a higher bid price than lower-cost supply regions, which could reduce competitiveness in EU-wide auctions. However, bids can emphasize demonstration value for supply-constrained regions (a common scenario across much of Europe where production infrastructure is not yet proximate to demand centres), island connectivity social benefits, and knowledge creation for replicability. Without Innovation Fund revenue support, the operational economics of Croatian cases are fundamentally challenged, as hydrogen procurement costs alone (€9-13/kg) plus operational overhead would exceed likely market revenue, making the premium not merely beneficial but essential for project viability. This creates significant dependency on auction outcomes, which cannot be guaranteed ex-ante and introduce material execution risk that must be acknowledged in financing planning

12.2.1.2.3 Interregional & Collaborative Platforms: North Adriatic Clean Hydrogen Investment Platform (NACHIP)

Split and Zadar, as part of Croatia's North Adriatic region, are connected to the NACHIP initiative, which supports hydrogen value-chain innovation across Croatia, Slovenia, and Italy. A €7.6 million ERDF grant was awarded to support hydrogen projects and SME integration in hydrogen value chains. While this is more innovation and acceleration focused, it provides a cascade financing opportunity at TRL 6–9 and can help integrate smaller partners or technology pilots into broader infrastructure work.

As discussed in Ch. 4.3.2, NACHIP's primary role is complementary funding for innovation/demonstration components rather than core infrastructure CAPEX. Potential applications for Split and Zadar HRS include advanced monitoring and digitalization systems (real-time hydrogen quality sensors, predictive maintenance platforms), enhanced safety innovations (beyond standard requirements), SME integration funding for Croatian equipment suppliers or service providers participating in HRS supply chain, and workforce training programmes. Beyond direct financing, NACHIP provides access to transnational knowledge networks connecting Croatian projects to Italian and Slovenian hydrogen initiatives, which could facilitate technical assistance, regulatory best practice sharing, and capacity building to address institutional learning curve constraints documented in the strategic context above.

Italy – Croatia



TransH2

12.2.1.2.4 Environmental and Energy Efficiency Fund (FZOEU)

The Croatian Environmental Protection and Energy Efficiency Fund runs grant schemes that can co-finance development of hydrogen fuelling (charging) stations alongside electric charging infrastructure: grants at ~40 % co-financing were provided along in last presented calls, although relatively small, which can complement larger funding packages for demonstration projects or smaller hydrogen refueling components linked to broader Zadar sustainable mobility plans.

Given the modest scale of FZOEU grants relative to total HRS CAPEX requirements, this funding source should be positioned as gap-filling rather than foundational. Target allocation might be €0.3M-€0.5M for specific components such as grid connection, electrical infrastructure (transformers, backup power), civil works (site preparation, foundations), or safety equipment (fire suppression, ventilation systems). Application approach could involve municipal or county co-applicants (City of Split/Zadar, Splitsko-dalmatinska županija / Zadarska županija) and framing as part of integrated port green transition encompassing HRS alongside shore power and electrification initiatives, which may strengthen eligibility within FZOEU programme objectives.

12.2.2 Broader National Mobility Strategy

Croatia's National Recovery and Resilience Plan (RRP) and national policy frameworks support hydrogen refuelling stations development by 2026 across the country, financially supported by the Ministry of Economy and the Ministry of Sea, Transport and Infrastructure.

CEF-linked support for hydrogen stations along TEN-T and strategic routes to expand alternative fuel infrastructure. This points to policy alignment and funding prioritisation that a Split or Zadar project could tap into by aligning with national decarbonisation strategy and TEN-T network planning.

The Croatian Hydrogen Strategy to 2050 (see Ch. 4.3.2) provides strategic policy backing for hydrogen infrastructure development, though specific implementation mechanisms and funding allocations are still being established. The INA Rijeka green hydrogen project (€45.5M total value, €15M RRP grant as per Ch. 4.3.2) demonstrates that Croatian RRP resources can support hydrogen infrastructure, with approximately 33% public co-financing in that case. While INA Rijeka focuses on production rather than refuelling infrastructure, the precedent suggests that RRP or sectoral maritime decarbonization budgets could potentially contribute 10-20% of HRS CAPEX (~€0.7M-€1.4M) if the project is positioned as integral to Croatian maritime decarbonization strategy and FuelEU Maritime compliance for state-subsidized island ferry services (Jadrolinija operations). This would require proactive engagement with Ministry of Sea, Transport and Infrastructure and Ministry of Economy to explore sectoral funding pathways or integration into national maritime decarbonization implementation plans. Such funding, while not currently confirmed for maritime HRS, cannot be excluded as a possibility given documented policy priorities and precedent resource mobilization.

Italy – Croatia



12.2.3 Local / Regional Context

12.2.3.1. Zadar & EU Funds Awareness

Currently there is no evidence about specific Zadar-only funding call for hydrogen infrastructure, local actors (City of Zadar, Zadarska županija, development agencies) are actively engaged in EU fund promotion and capacity building events to help stakeholders access EU programmes. This includes information campaigns and partnerships to increase project readiness for EU calls. This institutional engagement, while not translating to dedicated local funding at present, indicates capacity building trajectory and stakeholder awareness that can support project preparation and application processes. Local actors' familiarity with EU funding mechanisms may facilitate coordination for AFIF applications, national programme engagement, and PPP structuring, even absent direct municipal or county financial contribution. Should future regional or local funding opportunities emerge (analogous to FVG regional hydrogen calls documented in Section 4.3.1), the existing engagement infrastructure could enable rapid mobilization.

Source	Instrument / Programme	Role in Project	Typical Share	Key Notes for Zadar
EU Innovation Fund	Hydrogen Auction (€/kg premium)	Revenue support to bridge LCOH-market gap (covers OPEX + risk)	<i>Revenue support equivalent to 20–30% of project IRR uplift</i>	Particularly relevant if linked to green hydrogen production and maritime offtake; improves bankability but does not fund upfront CAPEX
CEF – AFIF (EU)	Grant + Blended finance	CAPEX co-financing for refuelling/ bunkering infrastructure	30–50% of eligible CAPEX	Strong fit for port-based infrastructure and TEN-T alignment; can be combined with national co-financing
Croatian National Hydrogen Programme	Direct national grants	Deployment of hydrogen refuelling stations	15–25% of CAPEX	National budget (~€29.6m) explicitly targets hydrogen stations; key anchor for Croatia-based HRS
Croatian RRP / Sectoral Funds	Recovery & resilience funding	Strategic infrastructure and clean mobility	10–20% of CAPEX	Best used if integrated into wider transport or port decarbonisation plans
Regional / Interregional (ERDF, NACHIP)	Cascade or complementary grants	Innovation, pilots, SME integration	5–10%	Useful for early deployment, digitalisation, safety systems, or cross-border Adriatic cooperation

Italy – Croatia



Public Partner (PPP)	Port authority / municipality contribution	Land, permits, basic infrastructure, equity	5–15% (in-kind + equity)	Port of Zadar can contribute land, grid access, demand aggregation, lowering project risk
Green / Blue Bonds	Thematic bond issuance	Long-term CAPEX financing	25–40% of total CAPEX	Attractive for port-related assets with long lifetimes; blue bond angle strengthens maritime narrative
Senior Debt (EIB / Banks)	Project finance loans	Remaining CAPEX financing	20–35%	Credit enhanced by grants, PPP structure and Innovation Fund revenue support
Private Equity	Sponsor / strategic investor	Risk capital, development and operations	10–20%	Typically energy, port services or hydrogen infrastructure operators

Table 3 - Example Optimal Financing Mix – Hydrogen Refuelling / Bunkering Station (Zadar)

12.2.3.2. ERDF Regional Programme 2021–2027 (Friuli Venezia Giulia)

The ERDF Regional Programme 2021–2027 of Friuli Venezia Giulia provides an illustrative example of how regional funding instruments within the EU may support the development of the hydrogen value chain. As part of the programme's flexibility allocation (€54.8 million), currently under discussion in the context of the Mid-Term Review (MTR), a portion of funding may be directed towards the renewable hydrogen sector. In particular, resources under Specific Objectives A1 and A6 could support research and innovation activities as well as investments in advanced technologies, while Objective B2 may support industrial projects and renewable energy infrastructure, in line with Directive (EU) 2018/2001.

While such instruments do not explicitly target hydrogen refuelling infrastructure, they demonstrate how ERDF programmes can contribute to enabling conditions for hydrogen deployment at regional level.

12.3 Summary of key findings

The potential implementation of hydrogen refuelling stations across selected port-related use cases within the Adriatic Sea basin has been assessed from an economic point of view. The analysis considers the current state of the art in terms of hydrogen demand, pricing dynamics, and the availability of supporting infrastructure at different territorial scales.

From a broader perspective, the analysis highlights a recognised need to further enhance and deploy dedicated hydrogen infrastructure, a condition that is closely linked to the establishment of an enabling framework for the uptake of hydrogen in transport applications, with particular reference to the maritime sector.

Within this context, a set of actions and pilot initiatives has been outlined. While Croatia is currently progressing towards the development of its first pilot installations, Italy is characterised by a more advanced level of engagement, reflecting a longer-standing involvement in hydrogen-related initiatives.

The architecture of the hydrogen refuelling station is connected to the most suitable form and the connected transport and logistic aspect. With this regard, the gaseous form supplied via tube trailers/trucks is the most realistic solution, even if it is not the cheapest in the long term compared to other solutions (e.g. pipelines, which require structured investment).

The topic of hydrogen propulsion is still under an intense research, development and innovation phase and availability of data and economic estimates are often fragmented and not available for all the use cases available. In these terms, the report integrates an aggregation of the most recent inputs and explains the significant impact of CAPEX costs on the equipment necessary for structuring the station. On the other side, OPEX are strictly related to the distance from the production point. In this regard, the Trieste use case could be facilitated by the availability of hydrogen production sites in the area, whereas the Zadar and Split use cases should consider the significant cost implications. In parallel, producing hydrogen on site would incur additional operating costs for Croatian use cases (production is not analysed in this report).

13. Applicability to Other Adriatic Ports

The business model of cooperation and the associated financial construction developed within the TransH2 project are explicitly designed to be **replicable across a wide range of Adriatic ports**, regardless of their size, governance structure, or current level of technological maturity. Replication does not require identical technical solutions or investment scales but is instead based on the transfer of governance principles, cooperation mechanisms, and phased financial logic.

Preconditions for Replication

Successful replication in other Adriatic ports requires a limited set of enabling preconditions rather than full system readiness. These include the presence of a port authority or port operator with a clear mandate for infrastructure planning, basic institutional capacity for cross-border or inter-regional cooperation, and alignment with national or regional decarbonisation and energy strategies. Importantly, full hydrogen infrastructure or vessel availability is **not a prerequisite** for replication; early replication can focus on planning, feasibility assessment, and stakeholder coordination. Ports with limited technical or financial capacity can enter the replication pathway at an early stage by adopting the cooperation framework, participating in knowledge-exchange networks, and aligning local development plans with the hydrogen transition objectives defined at cross-border level.

Stepwise Replication Pathway

Replication of the TransH2 model follows a **stepwise and modular pathway**, allowing ports to progress at different speeds depending on local conditions:

1. Strategic Alignment Phase

Ports assess compatibility with hydrogen-based maritime transport within their strategic and master planning documents, identify potential routes and users, and establish initial cooperation with regional authorities, neighbouring ports, and energy stakeholders.

2. Feasibility and Planning Phase

Technical, operational, safety, and economic feasibility studies are conducted using methodologies and tools developed within the TransH2 handbook. At this stage, ports benefit most from shared templates, joint studies, and peer learning with pilot ports.

3. Pilot Preparation Phase

Ports prepare for limited-scale pilot activities, such as temporary bunkering solutions, test operations, or shared hydrogen supply arrangements, often in cooperation with nearby ports or energy hubs.

4. Operational Scaling Phase

Once feasibility and regulatory conditions are confirmed, ports can move towards permanent infrastructure and regular hydrogen-fuelled operations, supported by hybrid financing mechanisms and long-term cooperation agreements.

This stepwise approach ensures that replication remains **proportionate and risk-aware**, preventing premature investment while maintaining momentum towards decarbonisation.

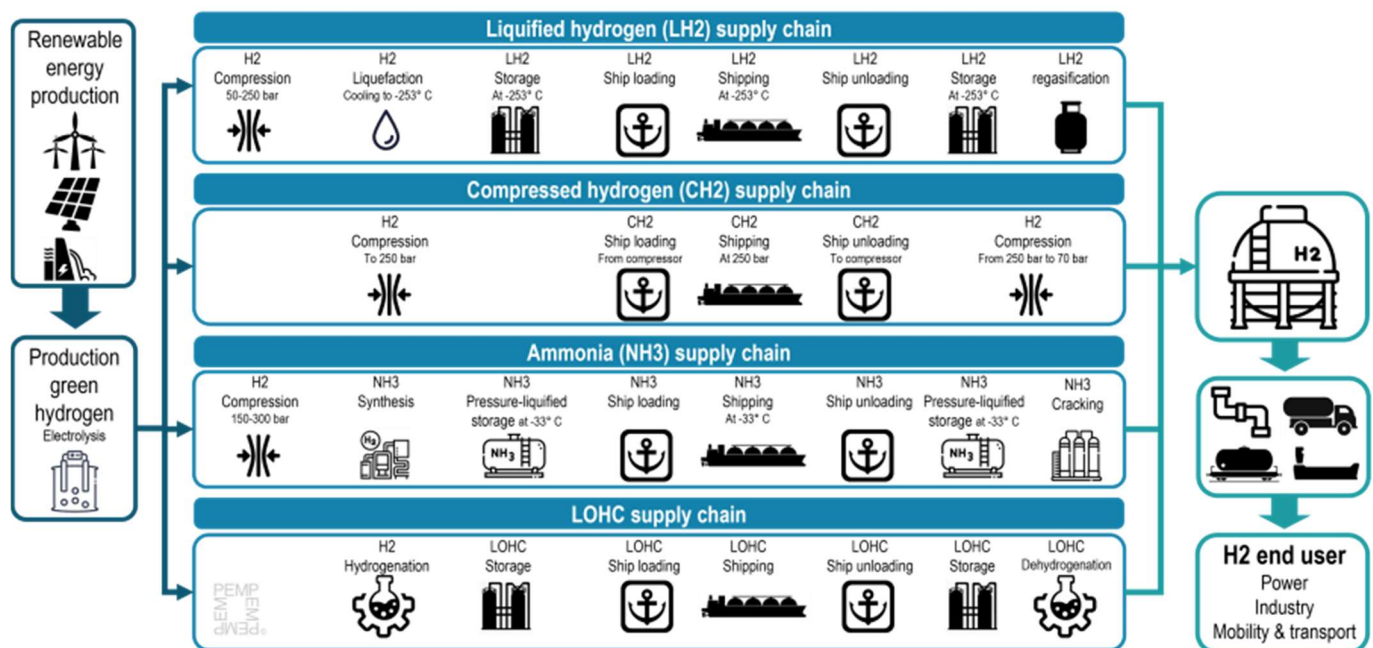


Figure 65. Operational scaling of TransH2 project

1. Adaptability to Port Size and Function

The TransH2 model is adaptable to different port typologies, including major passenger ports, regional ferry terminals, mixed-use ports, and smaller island or coastal ports. Larger ports may act as hydrogen hubs, hosting production, storage, and bunkering infrastructure, while smaller ports may rely on shared or mobile solutions and regional supply chains. Cooperation between ports of different sizes is therefore a central replication mechanism, enabling economies of scale and efficient use of infrastructure.

2. Transferability of Financial Logic

The financial construction is equally transferable, as it is based on **phased investment and blended financing** rather than fixed funding models. Replicating ports can initially rely on public funding for studies and planning, gradually integrating private investment as operational certainty increases. The

use of public-private partnerships, joint procurement, and coordinated investment planning can be replicated with adjustments to local legal and market conditions.

Importantly, replication does not require immediate financial self-sufficiency. Instead, it prioritises learning, risk reduction, and long-term cost competitiveness, which are common challenges across Adriatic ports.

3. Cross-Border Added Value of Replication

Replication across multiple Adriatic ports strengthens cross-border coherence, reduces regulatory fragmentation, and supports the emergence of interoperable hydrogen maritime corridors. By adopting a shared cooperation and financial framework, ports contribute to collective market formation, improve investment predictability, and enhance the strategic relevance of the Adriatic Sea within the broader European zero-emission transport network.

Through this replication-oriented approach, the TransH2 business model and financial construction serve not only as project outcomes but as **practical tools for long-term transformation** of maritime mobility across the Adriatic region.

To support practical replication, the TransH2 cooperation and financial model can be represented through a **replication matrix** that links three key dimensions:

- **Port typology** (size and functional role),
- **Hydrogen readiness and maturity level**, and
- **Recommended entry point into the TransH2 model.**

This matrix enables ports to identify *where to start*, *which actors to involve*, and *what type of financial construction is appropriate* at each stage.

Table 22: Replication Matrix Overview

Port Type	Hydrogen Maturity Level	Primary Entry Point	Cooperation Focus	Dominant Financial Logic
Large passenger / hub port	High / medium	Infrastructure & operations	Port authority, energy providers, operators, regulators	Blended finance, PPPs, long-term contracts
Regional passenger port	Medium	Pilot implementation	Port authority, ferry operators, research partners	Public co-financing + pilot CAPEX

Italy – Croatia



Port Type	Hydrogen Maturity Level	Primary Entry Point	Cooperation Focus	Dominant Financial Logic
Small regional or island port	Low	Strategic planning & feasibility	Regional authority, neighbouring ports, research partners	Public funding (studies, planning)
Mixed-use commercial port	Medium	Shared hydrogen services	Port operator, logistics firms, energy suppliers	Joint investments, shared assets
Emerging / future port	Low	Network participation	Regional and cross-border cooperation platforms	Public support, preparatory funding

Interpretation of the Matrix

Port Type Dimension

Ports differ significantly in scale, governance complexity, and operational scope. The TransH2 model does not prescribe a uniform solution but allows each port type to adopt a role consistent with its capacities. Larger ports are natural candidates for hydrogen hubs, while smaller ports benefit from networked solutions and shared infrastructure.

Maturity Level Dimension

Hydrogen maturity reflects not only infrastructure availability but also institutional readiness, regulatory familiarity, and stakeholder engagement. Ports with low maturity are encouraged to begin with strategic alignment and feasibility work, avoiding premature investment. Medium-maturity ports can transition into pilot actions, while high-maturity ports can support operational deployment and scaling.

Entry Point Dimension

The matrix highlights that replication does not start with infrastructure by default. Many ports will enter the TransH2 model through **planning, cooperation, and knowledge exchange**, progressively moving towards implementation. This staged entry is essential for financial sustainability and risk control.

Italy – Croatia



TransH2

Practical Use of the Matrix

For port authorities and regional planners, the replication matrix serves as:

- a **self-assessment tool** to determine readiness and next steps,
- a **decision-support instrument** for prioritising investments and partnerships,
- a **communication tool** to align stakeholders around realistic timelines and expectations.

For policy-makers and programme authorities, the matrix demonstrates how a single cooperation and financial framework can generate **differentiated yet coherent replication pathways**, reinforcing cross-border integration without imposing uniform solutions.

Contribution to Cross-Border Scalability

When applied collectively across multiple Adriatic ports, the replication matrix supports the gradual emergence of **interoperable hydrogen maritime corridors**. Ports at different maturity levels can participate simultaneously, each contributing according to its role, while benefiting from shared standards, coordinated investments, and cumulative learning effects.

In this way, the visual replication matrix operationalises the TransH2 cooperation and financial model, transforming it from a project-specific outcome into a **scalable and transferable framework** for the long-term decarbonisation of Adriatic maritime transport.

- End of the document -