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Hydrogen Powered Ferries in the Adriatic Sea: A Technical and Environmental Assessment

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Abstract. 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 Organization, the share of global Greenhouse Gas emissions from the maritime transportation sector has increased to almost 3%. From this context, this study focuses on the selection of representative maritime routes in the Adriatic Sea and the development of solutions for transitioning diesel-engine-powered to hydrogen-powered ferry vessel solutions. The objective is to assess the technical feasibility of hydrogen-based power generation (for all onboard utilities, including propulsion) by evaluating route and vessel characteristics, including environmental and fuel consumption aspects. The environmental evaluation encompasses air quality analysis, emphasizing pollutants such as SO_2, NO_2, CO, PM2.5, and PM10 in the involved port areas, Natura 2000 site assessments to identify ecologically sensitive zones, and CO_2 emissions avoidance calculations to quantify potential reductions from switching to hydrogen technology. The fuel consumption analysis estimates hydrogen demand based on vessel energy requirements. The results provide an environmental route profile, highlighting emissions and protected areas; and a fuel consumption route profile, detailing hydrogen demand for propulsion and auxiliary power. The findings offer effective insights for policymakers and industry stakeholders to facilitate the adoption of hydrogen-powered vessels in the Adriatic Sea, supporting the broader goal of maritime decarbonization.

Keywords. Hydrogen-powered vessels, Maritime decarbonization, Adriatic Sea route analysis, Air quality and environmental impact

1. Introduction

The maritime sector is responsible for a significant share of the global greenhouse gas (GHG) emissions, accounting for approximately 3% of total global emissions [1], which corresponds to around 1,076 million tonnes of CO_2, representing about 2.9% of global anthropogenic emissions. Projections suggest that the sector could reach up to 10% of

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global emissions by 2050 [2], if no measures are taken to reduce this effect. The majority of emissions comes from the combustion of fossil fuels, mainly heavy fuel oil (HFO) and marine diesel, used for propulsion and onboard energy demand. The steady increase in the demand for maritime transport has heightened pressure for the adoption of cleaner technologies, improvement of energy efficiency, and transition to alternative fuels such as hydrogen and ammonia. Decarbonization efforts, including regulatory measures by the International Maritime Organization (IMO), are essential to achieving the targets for emission reduction targets and aligning with the global climate agenda, such as the European Green Deal and the Paris Agreement.

The Adriatic Sea is an important European maritime corridor and is the stage for the maritime transport industry on the Croatian and eastern Italian coasts. It is a vital means of connection between the two countries, with significant shipping activity, particularly in the central and north regions, and a dense maritime traffic with numerous different routes (Figure 1), especially during the summer. Such an intense maritime traffic increases the potential for higher environmental impacts due to emissions from the vessels in the region. In fact, the growth of tourism in the region has resulted in an increased environmental burden, to the point that environmental costs in the region might be much higher than the economic benefits for local communities [3].

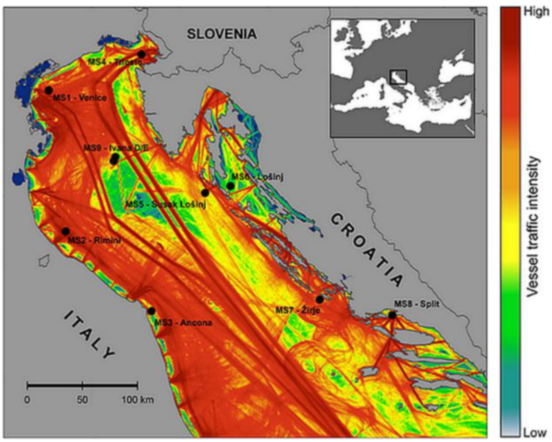


Figure 1. Vessel traffic intensity in the Adriatic sea [4].

The environmental impacts vary by port city, depending on harbour activities. Addressing this issue requires large-scale, transnational mitigation strategies to ensure environmental sustainability without compromising economic competitiveness [5]. In fact, according to Merico et al. [6], harbour activities significantly impact air quality in the Adriatic Sea, especially in Venice, where shipping emissions contribute notably to nanoparticle concentrations, posing health risks. Compared to Rijeka [7], Venice experiences higher particulate levels due to greater ship traffic and local meteorological conditions, while Rijeka is more affected by road traffic. Nanoparticles ($D < 0.25$ μm) are the most influenced by shipping, highlighting the need for improved monitoring. Similar trends in Brindisi and other Adriatic harbours indicate a regional concern.

Short maritime routes selection in the context of recent environmental impacts concerns has received little attention in the literature (especially the short regional routes). For instance, the work conducted by Pham et al. [8] was based on an analysis for long shipping route selection focusing mainly on the economic aspects of the each route. The study developed by Santos et al. [9] presented a methodology for designing short sea shipping routes in the coast region of Portugal, but focusing also on the improvement of economic aspects.

Therefore, one can see that the growing of the intense maritime traffic in the Adriatic Sea has the potential to exert further environmental impacts to the region and, consequently, to affect negatively the local communities throughout the region. Moreover, literature has given little attention to the short maritime routes selection in the context of the global energy transition. In such a context, this work has the aim to

- select representative maritime routes in the Adriatic Sea and develop solutions for replacing diesel-powered ferry vessels with hydrogen-powered ferry vessels;
- assess the technical feasibility of hydrogen-based power generation (for all onboard utilities, including propulsion) by evaluating route and vessel characteristics, including environmental and fuel consumption aspects.

The environmental evaluation encompasses air quality analysis, emphasizing pollutants such as SO_2, NO_2, CO, PM2.5, and PM10 in the involved port areas, Natura 2000 site assessments to identify ecologically sensitive zones, and calculation of avoided CO_2 emissions to quantify potential reductions from switching to hydrogen technology. The fuel consumption analysis estimates hydrogen demand based on vessel energy requirements.

This study has been developed within the TransH2 Interreg project [10], co-funded by the European Union, and contributes with the research, evaluation, and technology option analysis of selected maritime routes, located in the Adriatic Sea region, to be modernized by means of hydrogen onboard technologies. These routes were defined through the development of three phases, which are also explained in this work.

The work is structured as follows: section 2 introduces the TransH2 project and explains its main goals; section 3 describes the methodology used to develop each phase of the present study, while section 4 presents the selected maritime routes which were the main object of this study; section 5 provides the main obtained results whereas section 6 discusses the main conclusions from the work.

2. The TRANSH2 Interreg Project

The Transition to Hydrogen Fuelled Cross-Border Sea-Mobility (TransH2) project has the aim of enhancing the sustainability of sea-mobility in the Adriatic Sea region through the development of low-carbon transportation solutions for the modernization of representative maritime routes. Such modernization is investigated through the development of three case studies, one cross border maritime route and two regional maritime routes, in which low-carbon transportation solutions, specifically zero-emission fuels such as hydrogen, are analysed. By demonstrating the feasibility and benefits of these solutions, the project seeks to promote their adoption among port authorities, transport operators, and other stakeholders in the area.

Another important aim of the TransH2 project is to support the European Green Deal by significantly reducing maritime sector emissions through the development of hydrogen-fuelled vessels and infrastructure in Italy and Croatia. By integrating zero-emission hydrogen technology, the project aligns with the EU's goal of cutting maritime emissions by 90% by 2050 [11] and contributes to the mission of restoring ocean and water quality.

A key focus of TransH2 is establishing a complete hydrogen supply chain, including vessel development and port refuelling infrastructure, in line with the EU Sustainable and Smart Mobility Strategy's 2030 milestone for market-ready zero-emission vessels. Additionally, the project highlights the economic potential of hydrogen to drive innovation, create jobs, and diversify the regional economy.

Despite its promise, hydrogen adoption faces challenges such as high investment costs, regulatory requirements, and infrastructure needs. TransH2 emphasizes the importance of public-private collaboration to address these barriers. Through cross-border cooperation and knowledge exchange, the project aims to position the Adriatic region as a leader in sustainable maritime transport, setting a model for other European regions.

3. Methodology

In order to determine the final three routes (use-cases) for an in-depth analysis of zero-emission technical solutions, a structured step-by-step selection process was developed within the TransH2 project, which can be observed in Figure 2.

- **Initial Screening:** a total of 54 maritime routes were analysed, focusing on regional connections along the eastern Italian and Croatian coasts, as well as cross-border routes between Italy and Croatia. Data sources included previous Interreg projects, data from previous activities developed within TransH2 project itself, and other publicly available databases.
- **Preliminary Selection:** from the initial 54 routes, 17 were shortlisted based on key criteria such as vessel type, passenger flow, and travel time.
- **Workshop and survey with Stakeholders:** the 17 pre-selected routes were presented to stakeholders in an online workshop. Participants were introduced to the TransH2 project objectives and guided through the selection methodology. A structured questionnaire was designed and distributed to collect stakeholders' feedback, ensuring a balance between open discussion and targeted data collection. Attendees were encouraged to evaluate the proposed routes based on operational, social, economic and environmental priorities, with the final selection made according to their responses.

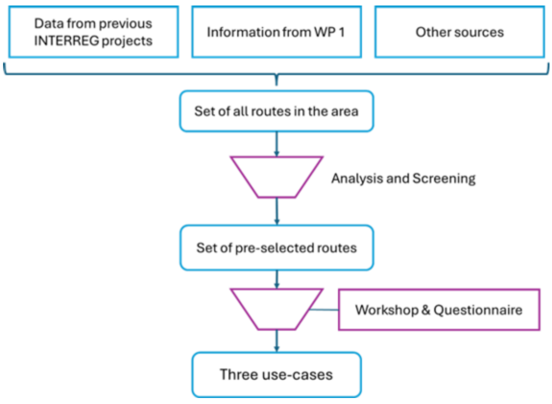
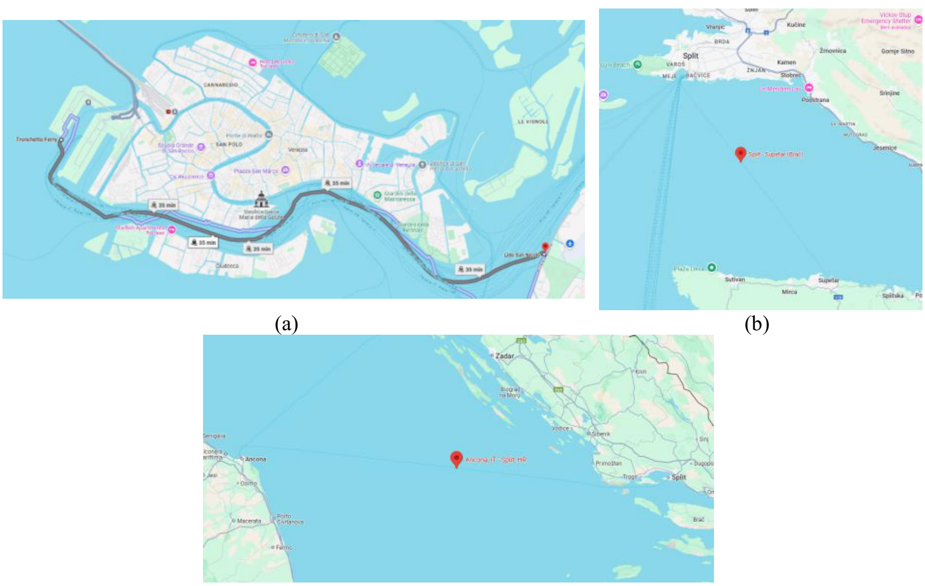


Figure 2. Workflow for the selection of the three maritime routes (use-cases).

The route selection process considered two key perspectives: environmental, and transportation characteristics. The environmental assessment focused on air quality conditions along the route, the presence of Natura 2000 protected areas, and the potential CO_2-equivalent emission reductions when adopting hydrogen-based solutions over conventional diesel engines. Additionally, regulatory constraints, such as International Maritime Organization conventions and local maritime regulations, were taken into account. Lastly, the transportation analysis addressed operational parameters, including route distance, service frequency, vessel speed, the installed capacity of hydrogen-powered systems, and fuel consumption.

4. Selected Maritime Routes

As mentioned in section 3, 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 maritime routes in the Adriatic Sea to be subject to further investigation for the transition towards hydrogen technologies. The three maritime routes (Figure 3) are: Tronchetto-Lido, Split-Supetar, and Ancona-Split.



(a) (b)

(c)

Figure 3. Selected maritime routes. Tronchetto-Lido (a), Split-Supetar (b), and Ancona-Split (c).

5. Results and Discussion

5.1. Environmental Analysis

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. 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, the present work focuses on solely evaluating the concentration of key pollutants in the areas related to the three selected maritime routes.

Table 1 presents key air quality parameters for the areas related to each selected maritime route. These are the most recent (for 2023) public available data from the ARPAV [12], the Ministry of Environmental Protection and Green Transition of Croatia [13], and the ARPAM [14]. The current scenario presents a positive overall evaluation for the analysed parameters, although some of them have reached values beyond the regulated daily average limit. This is the case of NO_2, PM2.5, and PM10, which have extrapolated the daily regulated limit for some periods in 2023.

Table 1. Air quality parameters for the three selected maritime routes. Abbreviations: Regulatory daily average limit (R); Measured daily average (M).

		Tronchetto-Lido		*Split-Supetar*		*Ancona-Split*	
Parameter	*Unit*	**R**	**M**	**R**	**M**	**R**	**M**
SO_2	*µg/m³*	125	10	125	8	125	5
NO_2	*µg/m³*	40	26 to 36	40	18	40	15
CO	*mg/m³*	10	1	10	0.5	10	0.4
PM2.5	*µg/m³*	25	20	25	10	20	14
PM10	*µg/m³*	40	29 to 32	50	20	40	20

For what concerns the Natura 2000 sites, only the Tronchetto-Lido route operates close to Natura 2000 sites designated within the Venice Lagoon. At some point, the mentioned route crosses one of these sites. The other two routes do not cross any Natura 2000 site, although at some point they operates relatively close to some protected areas. Therefore, reducing emissions, such as by adopting hydrogen-powered ferries, would benefit these ecologically protected areas.

The calculation of not only the avoided CO_2 emissions, but also the avoided emissions from other pollutants, has been conducted by considering that, during the operation phase, hydrogen-powered ferries do not emit any of the analysed pollutants. Therefore, the avoided emissions for each selected route are reported in Table 2, considering (i) the typical Diesel engines used in the ferry boats operating in such routes and (ii) the typical marine Diesel type used in these engines.

Table 2. Emissions regarding the operation phase for typical Diesel-engine-powered ferry boats operating in each selected route.

	kg CO_2	*kg SO_X*	*kg NO_X*	*kg PM*
*Tronchetto-Lido**	17,136	16.8	268.8	5
*Split-Supetar**	53,558	42.7	817.4	17
*Ancona-Split***	1,114,085	917.4	16,993	354

* weekly emission values for the entire operation from point A to B.
** yearly emission values for the hotelling phase.

5.2. Hydrogen Consumption

The analysis of fuel consumption and the resulting emissions (presented on Table 2) from ferries operating on the selected maritime routes was 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. Table 3 presents the hydrogen consumption for each selected route. For the routes Tronchetto-Lido e Split-Supetar, the values refer to an average weekly consumption. For the route Ancona-Split, the value refers to a 12-hour period of hotelling.

Table 3. Hydrogen consumption for each selected route.

	H_2 consumption (kg)	
	Low season	High season
*Tronchetto-Lido**	1176	1176
*Split-Supetar**	4514	7252
*Ancona-Split***	-	720

* weekly consumption values for the entire operation from point A to B.
** 12-hour consumption for the hotelling phase.

6. Conclusions

The paper presented a study regarding the selection of short regional maritime routes in the context of the global energy transition. The main objectives were (i) the definition of maritime representative routes, within the Adriatic Sea, with the aim to develop solutions for adopting hydrogen-powered ferry vessels and (ii) the assessment of both the environmental impact and hydrogen consumption aspects for each selected route.

Besides the procedure for selecting each route, the study demonstrated potential benefits for the improvement of local air quality measurements and for the local affected Natura 2000 sites. Moreover, the work also provided a preliminary quantification regarding the hydrogen consumption for each selected route. A further study will evaluate in depth the hydrogen technology options for each ferry boat operating in each selected route.

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