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SHIP FEASIBILITY STUDY

SHIP FEASIBILITY STUDY, D 2.1

Authors: LDCK - WP leader, PFRI task leader, other partners involved MCoE, TECO, DNV, LDCK, Jadrolinija, TU Chemitz

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ACRONYMS

ABS	American Bureau of Shipping
ACT	Advanced clean transportation
AF	Application Form
AFC	Alkaline Fuel Cell
AFID	Alternative Fuels Infrastructure Directive
AMSA	Australian Maritime Safety Authority
ASME	American Society of Mechanical Engineers
bar	Unit per pressure
BV	Bureau Veritas
CA	Consortium Agreement
CAPEX	Capital expenditure
CCS	The China Classification Society
CI	Compression ignition
CLASSNK	The Nippon Kaiji Kyokai
COX	Carbon dioxide
DNV	Det Norske Veritas
DMFC	Direct methanol fuel cell
DWT	Deadweight tonnage
EEDI	Energy Efficiency Design Index
EMSA	European Maritime Safety Agency
EPRI	Electric Power Research Institute
ETS	Emissions Trading System
EU	European Union
Etc.	Et cetera (and so on)
FC	Fuel cell
FDIR	Fault Detection, Isolation and Response
FTP Code	International Code for the Application of Fire Test Procedures
GH2	Green hydrogen
GHG	Greenhouse gas
GRIP	Green innovation platform
GW	gigawatt
h	hour
H2	Hydrogen
HB	Handbook
HDPE	high-density polyethylene
HFCS	Hydrogen fuel cells
HT-PEMFC	High Temperature Proton Exchange Membrane Fuel Cell
HySUT	The Association of Hydrogen Supply and Utilization Technology
ICE	Internal combustion engine
i.e.	Id est. (that is)
IEA	International energy agency
IGF Code	International Code of Safety for Ships using Gases or other Low-flashpoint Fuels
IMO	International Maritime Organization

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IRENA	International Renewable Energy agency
ISO	International Organization for Standardization
Kg	kilogramme
Kn	Knots
KR	Korean Register
L	litre
LH2	Liquid hydrogen
LNG LOTO	Liquified natural gas Lockout
LR	Lloyd’s Register
m	meter
MARPOL	International Convention for the Prevention of Pollution from Ships
MCFC	Molten Carbonate Fuel Cell
MEP	Mechanical, electrical and plumbing
Mg	magnesium
MPa	megapascal
MW	megawatt
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
Nm	Nautical mile
NOX	Nitrogen oxides
OPEX	Operational expenditure
PA	polyamide
PAFC	Phosphoric acid fuel cell
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
PSI	Pounds per square inch
RED	Renewable Energy Directive
RO-PAX ferry	Roll-on/roll-off ferry
RPM	Revolutions per minute
SI	Spark ignition
SOX	Sulfur oxides
SOFC	Solid Oxide Fuel Cell
SOLAS	International Convention for the Safety of Life at Sea
SWOT	Strengths, weaknesses, opportunities, and threats
TCO	Total cost of ownership
TEN-T Traffic Routes	Trans-European Transport Network Traffic Routes
UK	United Kingdom
USNWG	United States National Work Group
ZEAS	Zero Emission Adriatic Ship

1 EXECUTIVE SUMMARY

The purpose of the feasibility study is to examine and evaluate solutions as appropriate for the implementation of the hydrogen-powered ship in accordance with the basic requirements of the ZEAS project, namely to develop green hydrogen propulsion and powertrain on a newly built passenger ship which should be approximately 38 m long with the target capacity for 250 passengers.

The feasibility study considered and evaluated options for utilizing hydrogen as a fuel for powering the ship intended to navigate at some of the domestic (Croatian) passenger lines. According to a preliminary examination of the potential lines by the consortium partner Jadrolinija, four lines have been chosen as appropriate. Those lines are lines where passenger ships with similar dimensions and passenger capacity to those proposed for ZEAS project currently operate. Passenger lines are elaborated as follows, Zadar – Preko, Mali Lošinj – Vele Srakane – Unije – Susak, Vodice – Prvić Šepurine – Prvić Luka – Zlarin – Šibenik and Suđurađ (Šipan) – Lopud – Koločep – Dubrovnik.

The study examined the legal framework that has been already introduced for hydrogen-powered ships as well as those that are currently under development that can be applied to ZEAS ships.

Furthermore, the document studies different technologies and options for ships' propulsion options specifically types of hydrogen fuel cells. Based on design requirements for the development of hydrogen-fuelled ships some options and solutions for the determination of onboard hydrogen storage methods, analysis of various technical issues, ship and fuel systems, expenses for different solutions and other relevant aspects are presented.

2 INTRODUCTION: BACKGROUND, RELEVANCE AND DOCUMENT STRUCTURE

The IMO GHG strategy proposed a decrease in CO_2 emission by at least 40% by 2030 and at least 70% by 2050. The necessity for CO2-neutral powertrains to have the lowest possible emissions compared to other regulated engine exhaust components is crucial for the diversification of future fuels. While current alternative fuels such as ethanol, methanol, biodiesel, propane, natural gas can reduce engine emissions to varying degrees compared to conventional liquid hydrocarbon fuels, hydrogen stands out as a potentially emissions-free energy carrier.

Currently, in the Republic of Croatia there is no infrastructure for the use of hydrogen in shipping, and according to the "*The Croatian National Policy Framework for the deployment of the infrastructure and the development of the market for alternative fuels in transport (NPF)*", is not specified. However, there were certain developments, Croatia has included hydrogen in the "Croatian Integrated National Energy and Climate Plan for the period 2021-2030", and the "*Strategy for Hydrogen Development*" clearly outlines the path of development of renewable hydrogen from production, through distribution to consumption, both in the transport sector (where the situation is most mature) all the way to industry. Furthermore, through the National Recovery and Resilience Plan, Investment C1.2. R1-I3 covers the production of renewable hydrogen (construction of a 10 MW electrolyser) and the establishment of infrastructure for renewable energy in transport (6 hydrogen filling stations and infrastructure for distributing hydrogen to the transport sector) worth around EUR 26,5 million. The investment is in the preparatory phase, and its realization will, in addition to the decarbonization of the energy sector and the achievement of the goal of reducing traffic emissions, also ensure the development of new economic activities in Croatia. Also, this investment will bring Croatia's energy policy into line with the Green Plan and the goal of a decarbonized Europe by 2050. The networks of hydrogen filling stations (construction of the first six filling stations) are planned on the TEN-T transport routes while part of the filling stations would also be provided to public transport companies.

On the other side new Croatian strategy for the use of Hydrogen till 2050 explicitly says that it is necessary to build an appropriate infrastructure for the production, distribution and supply of hydrogen, and at the same time encourage the development of ships that use hydrogen as a fuel aiming creation increased demand for hydrogen. The development of hydrogen-powered ships needs to be accompanied by relevant regulations. In that sense strategy also states that harmonization and introduction of international standards for the application of hydrogen should include the Croatian Register of Shipping.

This study considered and evaluated options for utilizing hydrogen as a fuel for powering the ship intended to navigate at one of the domestic (Croatian) passenger lines and consists of 6 chapters dealing with the hydrogen applications, and legal framework for hydrogen-powered ships, ship assessment technical feasibility, use of fuel cells as well as analysis of H2 engines technology. The document also explains the fuelling and storage facility and describes potential lines where ZEAS ship could be operated.

3 ANALYSIS

3.1 Hydrogen Applications

Hydrogen as a fuel assumes its use in propulsion units to produce electricity in a quantity sufficient to run the ship.

A fuel cell is an electrochemical device that is used to convert chemical energy into direct current, and heat and water appear as by-products. It consists of an electrolyte, which is located between two electrodes. Hydrogen, which is the most common fuel in fuel cells, passes through one electrode, the anode, while oxygen passes through the other electrode, the cathode. With the help of the catalyst, the hydrogen atoms are electrically separated at the anode, and free electrons are created, which go to the cathode through the electrical conductor via the consumer. In order to accelerate the reactions on the electrodes, they are covered with a layer of catalyst, and the catalyst depends on the type of fuel cell. The positive nucleus of the hydrogen atom also goes to the cathode through the electrolyte. After that, hydrogen atoms are regenerated, which takes place at the hydrogen cathode itself, and thus combines with oxygen molecules, and as a result, thermal energy and water vapor are generated. The process itself is clean, quiet and very efficient.

According to the principle of operation, the fuel cell is similar to batteries, but unlike them, they require a constant supply of fuel and oxygen. In this case, the fuel can be hydrogen, synthetic gas (a mixture of hydrogen and carbon dioxide), natural gas or methanol, and the products of their reaction with oxygen are water, electric current and heat, and the whole process is, in fact, the opposite of the electrolysis of water. The electrolyte that induces the electrochemical reaction in the fuel article can be composed of a liquid or solid medium.

At the moment, there are several different technologies for generating electricity with the help of hydrogen.

In general, the main advantages of using hydrogen in fuel cells for electricity generation are:

- high energy value of hydrogen and high efficiency of fuel cell,
- energy conversion without moving parts,
- low noise level and no or very small amounts of harmful exhaust gases,
- renewable and unlimited amounts of hydrogen available in various fuels/compounds,
- does not produce harmful substances in the reaction with oxygen, the only by-product is water,
- non-toxic and does not pollute the environment,
- easier storage and preservation compared to electricity.

The main disadvantages of using hydrogen are:

- depending on the production method of hydrogen it requires a relatively lot of energy, so it still causes air pollution with carbon dioxide and other harmful gases, if not produced as green hydrogen (by using wind or solar power),
- hydrogen transport, storage, and distribution on board are currently challenging from the point of safety and technology;
- lack of supply infrastructure,
- unfavourable ratio of price, power and mass,
- still not completely known behaviour in ship conditions (humidity, salty air, a wide range of ambient temperatures, vibrations, rolling off the ship, etc.).

The use of fuel cells in the marine industry must meet the requirements of the ship's electrical power generation device and the requirements related to the layout and construction of fuel handling systems such as piping, materials, and storage.

The first hydrogen-fuelled ship was built in 2000. It is designed as a passenger ship. From that time the number of ships has gradually increased and currently, the number of hydrogen-powered ships in operation is relatively small. In 2023 a total of 41 hydrogen-powered ships were in the testing phase or were operational. The building of new ships has dramatically increased in the last several years when almost 50% (from 2021) of all hydrogen-powered ships have been built. Almost half of all ships are operational in Europe.

Typical hydrogen-powered ships are relatively small passenger ships with lengths up to 50 m.

It should be mentioned that compressed hydrogen storage is the prevailing method for on-board fuel storage but also some ships use cryogenic liquid hydrogen or a material-based method of storage (hybrid).

The existing supply of H2 - Currently, there is no infrastructure for the use of hydrogen for the marine industry and applications in the Republic of Croatia, and as already mentioned according to the "*The Croatian National Policy Framework for the deployment of the infrastructure and the development of the market for alternative fuels in transport (NPF)*", is not specified.

As already mentioned, there are certain developments, given that in July 2021, the EU strategy for hydrogen was published, which sets the goal of building a minimum of 6 GW of electrolysers to produce green hydrogen in the EU by 2024, and 40 GW of electrolysers by 2030. Croatia has included hydrogen in the National Energy and Climate Plan, and the Strategy for Hydrogen Development clearly outlines the development path of renewable hydrogen from production, through distribution to consumption in the transport sector (where the situation is most mature) all the way to industry. Furthermore, through the National Recovery and Resilience Plan 2021-2026, Investment C1.2. R1-I3 covers the production of renewable hydrogen (construction of a 10 MW electrolyser) and the establishment of infrastructure for renewable energy in transport (6 hydrogen filling stations and infrastructure for distributing hydrogen to the transport sector) worth around 26,5 mil. EUR. In addition, it is planned to encourage the infrastructure for electric vehicles worth 6,6 million EUR and over 13 million EUR for a pilot project that will enable the development and commercialization of the CO_2 capture and storage process. The investment is in the preparatory phase, and its realization will, in addition to the decarbonization of the energy sector and the achievement of the goal of reducing traffic emissions, also ensure the development of new economic activities in Croatia. Also, this investment will bring Croatia's energy policy into line with the Green Plan and the goal of a decarbonized Europe by 2050.

The networks of hydrogen filling stations (construction of the first six filling stations) are planned on the TEN-T transport routes while part of the filling stations would also be provided to public transport companies.

The decision on the line where the Jadrolinija hydrogen-fuelled ship will sail should be followed with the appropriate location of the filling stations.

3.2 Legal framework

A comprehensive legal framework specifically designed for hydrogen-powered ships is currently lacking but is starting to be developed. Several international, regional and national regulations, standards and guidelines, including those issued by classification societies, play a key role in defining the parameters for their development, certification and operationalization.

This chapter aims to provide a detailed overview of the constituent elements that make up the regulatory framework relevant to hydrogen-powered ships, including regulations from classification societies, national authorities and the European Union (EU). By analysing in detail, the interactions between international conventions, regional directives and guidelines established by classification societies, we aim to offer insights into the legislative framework governing hydrogen-powered ships.

Internationally recognized regulatory frameworks related to hydrogen-powered ships are developing by the International Maritime Organization and the classification societies.

3.2.1 IMO regulations

The International Convention for the Safety of Life at Sea (SOLAS) sets minimum safety standards for the construction, equipment, and operation of ships, including those using alternative fuels. While SOLAS does not specifically address hydrogen-powered ships, its general provisions apply to ensure the safety of all ships, including those using new technologies like hydrogen fuel cells, especially regulation II-1/55 Alternative Design and Arrangement.

The IGF Code (Code of Safety for Ships using Gases or other Low-flashpoint Fuels) adopted by the IMO currently contains detailed requirements only for natural gas as fuel for use in engines, steam generators and gas turbines. The requirements for fuel cells are under development and probably will represent a new part of the IGF Code. Until it enters into force, the requirements of the SOLAS Convention related to the same level of safety must be respected. Also, an alternative design method should be used according to IGF Code Part A: 2.3, which states “The equivalence of the alternative design shall be demonstrated as specified in SOLAS (International Convention for the Safety of Life at Sea) regulation II-1/55 and approved by the Administration.”

Additionally, the IMO developed several Guidelines for the use of alternative fuels. Namely, those guidelines are:

- The „Revised Guidelines on Alternative Design and Arrangements (MSC.1/Circ.1212-Rev.1, 2019.)“ for SOLAS Chapters II-1 (Construction - Subdivision and Stability, Machinery and Electrical Installations and III (Life-Saving Appliances and Arrangements) and MSC1/Circ. 1455 (Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments).
- The „Interim Guidelines for the Safety of Ships Using Fuel Cell Power Installations (MSC.1/Circ. 1647)”, June 2022. These guidelines aim to ensure the safe operation of hydrogen-powered ships by providing technical recommendations for their arrangement, installation, and operation.
- During implementing SOLAS regulation II-1/55, MSC.1/Circ.1212 “Guidelines on alternative design and arrangements for SOLAS chapters II-1 and III” and MSC.1/Circ.1455 “Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments”, shall be consulted.

The aforementioned IMO regulations and guidelines do not address fully all requirements for hydrogen-fuelled ships, especially those for storage and bunkering procedures on ships. Because of that, at the moment, drafting of the Interim guidelines for the safety of ships using Hydrogen (as well as Ammonia) as fuel is currently under development by the IMO CCC Sub-committee (Sub-Committee on Carriage of Cargoes and Containers). In addition, the IGF Code correspondence group is drafting the full requirements for hydrogen fuel cell-powered ships, which are expected to be finalized by 2025.

While these IMO regulations and guidelines provide a basic framework for the safe use of hydrogen-powered ships, ongoing developments in hydrogen technology inevitably require further updates of the regulatory framework.

3.2.2 Classification Societies

Certain classification societies have developed rules covering fuel cells, and standards for fuel cells on land and sea. Also, the standards related to the loading of fuel on ships refer only to LNG fuel, and the safety of the ship, crew and equipment has not been fully prepared in the event of certain accidents.

Recognizing the increasing interest in hydrogen as a fuel, multiple classification societies, such as ABS, Lloyd's Register, Bureau Veritas, DNV, CCS, ClassNK, and Korean Register, have recently issued rules and guidelines for the use of hydrogen as a marine fuel. These documents are listed and briefly described below.

Table 1 Regulations and guidelines issued by the classification societies – an overview

CS	Document	Year
American Bureau of Shipping (ABS)	Requirements for Hydrogen Fuelled Vessel	2023
	Guide for Gas and Other Low-Flashpoint Fuel Ready Vessels	2022
	Guide for Fuel Cell Power Systems for Marine and Offshore Applications	2019
Lloyd's Register (LR)	Rules and Regulations for the Classification of Ships utilizing Gases or other Low-flashpoint Fuels	2023
	Appendix LR 3 - Requirements for Ships Using Hydrogen as Fuel	2023
Bureau Veritas (BV)	Rules for hydrogen-fuelled ships (NR 678)	2023
	Regulations on fuel cell power systems (NR 547)	2022
Det Norske Veritas (DNV)	Rules Part 6 Chapter 2 Section 3: Fuel Cell Installations	2022
	Handbook for hydrogen-fuelled shipping	2021
The China Classification Society (CCS)	Guidelines for Ships Using Fuel Cell Power Installations	2022
The Korean Register (KR)	Guidance for fuel cell systems on board ships	2022
The Nippon Kaiji Kyokai (ClassNK)	Guidelines for Liquefied Hydrogen Carriers	2017

- The American Bureau of Shipping (ABS), - "Requirements for Hydrogen Fuelled Vessels (2023)". The document presents comprehensive guidelines tailored for ships powered by hydrogen and bearing the low flash point fuel notation. These standards, which draw from the IGF Code, offer specific provisions for the handling of both liquid and gaseous hydrogen.
    - Additionally, ABS introduced the "Guide for Gas and Other Low-Flashpoint Fuel Ready Vessels" in March 2022. This guide provides detailed instructions for vessels prepared to utilize alternative low-flashpoint fuels such as hydrogen, Compressed and Liquified Natural Gas (CNG and LNG), Ethane, LPG, Dimethyl Ether (DME), Methanol, Ethanol, Hydrogen or Ammonia).
    - ABS also issued the "Guide for Fuel Cell Power Systems for Marine and Offshore Applications" in November 2019
- Lloyd's Register (LR) "Rules and Regulations for the Classification of Ships utilizing Gases or other Low-flashpoint Fuels" (e.g., Methanol, Ammonia, and Hydrogen), is effective from 1 July 2023. It is complemented by Appendix LR 3 - Requirements for Ships Using Hydrogen as Fuel. This appendix provides complex guidance for the safe and effective functioning of ships utilizing hydrogen as a primary energy source.

- Bureau Veritas (BV) launched its inaugural classification „Rules for hydrogen-fuelled ships (NR678)“ in November 2023. These rules are aimed at facilitating the safe integration of hydrogen propulsion stipulating specific requirements for bunkering, storage, distribution, and utilization of hydrogen as a fuel onboard ships. Additionally, the rules cover "hydrogen-prepared" ships, which are designed to accommodate future installation of hydrogen fuel systems. NR678 document complements BV's existing regulations on fuel cell power systems (NR 547 published in January 2022).
- Det Norske Veritas (DNV) released its “Handbook for hydrogen-fuelled shipping“ in June 2021, offering detailed guidance on the technical and safety aspects of implementing hydrogen propulsion on ships. The document encompasses design principles, safety protocols, regulatory compliance, and operational strategies. In addition, in 2022. DNV issued Rules Part 6 Chapter 2 Section 3: Fuel Cell Installations.
- The China Classification Society (CCS) released its „Guidelines for Ships Using Fuel Cell Power Installations“ in 2022. The document refers to ships longer than 20 m equipped with fuel cell (FC) power installations or prepared for hydrogen fuel cell power installations.
- The Nippon Kaiji Kyokai (ClassNK) released its „Guidelines for Liquefied Hydrogen Carriers“ in March 2017. The guidelines provide standards and recommendations for the design, construction and operation of ships that transport liquefied hydrogen.
- In 2022. The Korean Register (KR) released its comprehensive „Guidance for fuel cell systems on board ships“. The guidance regulates the design, installation, and operation of fuel cell power systems covering various technical aspects such as system integration, safety measures, regulatory compliance, and operational procedures .KR also issued its „Rules and Guidance for the Classification of Ships Using Low-flashpoint Fuels“, offering detailed standards and recommendations for designing, constructing, and operating ships powered by low-flashpoint fuels. These guidelines address a range of technical considerations to ensure the safety and compliance of ships utilizing alternative fuels like methanol, ammonia, and hydrogen. KR also issued „Guidelines for Selection of Metallic Materials of Containment Systems for Alternative Fuels for Ships“.

One of the most important topics that require new hydrogen-powered ships is classification rules for a new ship. At this moment Croatian Register of Shipping is responsible for the classification of ships in national waters and does not have developed rules for hydrogen-powered ships. This should be developed in parallel with the development of the ship design project.

Croatian strategy for use of Hydrogen until 2050. state that the introduction of international standards for the application of hydrogen in transport, e.g. standards for hydrogen filling stations, hydrogen quality, calibration standards, approvals for vehicles (e.g. road transport), and for ships, should include the Croatian Ship Register.

3.2.3 EU regulation and national regulations in other countries

In 2023, The European Maritime Safety Agency (EMSA) published the report “Potential of hydrogen as a Fuel for Shipping”, in which the analysis of technical, environmental, and safety interconnections of the hydrogen-powered ships and legal framework are presented. The report studied the current production capacities of hydrogen, the existing regulatory framework for hydrogen applications in the maritime industry, options for fuel storage, supply, and energy generation technologies, and techno-economic analyses and risk-based case studies.

While there might be no regulations specifically designed for hydrogen-powered ships, some of the EU directives, policies, and initiatives have an indirect impact on hydrogen ships' implementation and operation.

The most relevant EU regulations and initiatives crucial for hydrogen ships are thus as follows:

- The Fit for 55 package as a result of the European Commission's presentation on July 2021 is an encompassing legislative proposal package developed to align to the greenhouse gas emission reduction effort of at least 55% by 2030 to 1990 levels. Among other elements, the package extends the territorial coverage of the EU Emissions Trading System (ETS) in particular sectors, including time transport. The ETS' carbon pricing mechanisms imply mission ease of clean propulsion technologies and thus could promote the adoption of hydrogen-powered ships to reduce exhaust emissions.
- The Fuel Maritime initiative, critical for decarbonizing the maritime sector because it promotes the application of sustainable alternative fuels, also plays an essential role in the composition of the Fit for 55 package. Fuel Maritime initiative does not explicitly focus on hydrogen-powered ships but rather establishes targets for hydrogen and sustainable fuels in maritime transport. The key is the substantial reduction of the GHG emission level from maritime traffic by as early as 2030. In addition, the package includes provisions aimed at encouraging the development of infrastructure for alternative fuels, reflected in the installation of hydrogen refuelling stations. Although the focus is primarily on land transport, the development of hydrogen infrastructure in ports can act as a catalyst for the widespread use of hydrogen-powered ships through the installation of basic refuelling facilities.
- The European Green Deal, presented in 2019, is a policy framework of the European Commission aimed at making the European Union's economy sustainable. It includes various initiatives to achieve carbon neutrality by 2050, including measures to promote renewable energy, energy efficiency and sustainable transport. Although the European Green Deal does not specifically target hydrogen-powered ships, it creates a favourable environment for their development by prioritizing clean energy and reducing emissions in all sectors, including maritime transport.
- The Alternative Fuel Infrastructure Directive – AFID – Directive 2014/94/EU, which was adopted in 2014, stipulates the necessity to develop alternative fuel infrastructure pathways, including hydrogen, across the EU. This directive focuses primarily on road transport but also requires member states to install refuelling infrastructure, including hydrogen refuelling stations in ports that are likely to sustain the rise of hydrogen-powered ships. The facilities are essential to influence the transition of hydrogen-powered ship expansion and decarbonization of maritime transport.

- The Renewable Energy Directive RED**,** namely its updated version EU/2023/2413, which came into legal force in November 2023, stipulates a vast number of terms in the field of renewable sources be implemented in all parts of the EU economy. The Directive presents binding targets and a regulatory framework for the utilization of renewable sources, fostering cooperation among the EU members in advancing to a sustainable energy status. Consequently, even though the RED does name hydrogen-powered ships, its mission provides for setting conditions is aimed to increase the deployment of renewable sources to the fields, historically dependent on gas consumption. Resistible hydrogen represents a renewable gas capable of reducing emissions.
- Launched in 2020, the European Clean Hydrogen Alliance promotes cooperation between stakeholders for the deployment of renewable and low-carbon hydrogen technologies The Alliance aims to expand renewable and low-carbon hydrogen production, develop a comprehensive hydrogen value chain, establish a supportive regulatory framework and facilitate international cooperation to promote global hydrogen deployment to integrate hydrogen-powered ships into the wider maritime sector.
- The Hydrogen Strategy for a Climate Neutral Europe, adopted in 2020, is the EU's plan to use hydrogen as a clean energy source. The strategy focuses on producing more hydrogen from renewable sources, building the necessary infrastructure, establishing regulations and working with other countries to promote the use of hydrogen worldwide. By promoting the decarbonization agenda and striving for climate neutrality in maritime operations, this strategy can facilitate the incorporation of hydrogen-powered ships.

Whilst the EU's impact on regulations for ships powered by hydrogen is considerable, it should be noted that local and national rules also play a substantial part.

Regarding the ZEAS project and its implementation, the most promising legal framework for the development of hydrogen-powered ships to consider will be Interim guidelines for the safety of ships using Hydrogen as fuel and full requirements for hydrogen fuel cell-powered ships currently under development by the IMO. In addition, one of the classification rules that have already been developed for hydrogen-powered ships should be implemented, while waiting for the Croatian Register of Shipping, a classification society responsible for the classification of ships in national waters, to develop rules for hydrogen-powered ships.

4 SHIP ASSESSMENT TECHNICAL FEASIBILITY

The technical assessment objective is to present hydrogen storage and propulsion technologies used on existing ships as well as the accompanying infrastructures on shore for refuelling purposes and then to evaluate this according to ZEAS consortium solutions. The advantage is given to technologies and systems in a commercial-ready or near-commercial-ready stage. Thus, the technical assessment is divided into two distinctive parts:

- the ship design and propulsion, and
- refuelling infrastructure.

At the end of each assessment, the proposal of the recommended technology or system is provided.

4.1 Ship design and propulsion

Introducing hydrogen as the future of a ship’s fuel and propulsion represents a paradigm shift in the maritime industry. Many maritime industry leaders, manufacturers and research institutions investigate the numerous possible solutions in all hydrogen propulsion aspects, which can significantly differ in technical and technological approaches. Thus, it is important to know the ship design criteria i.e. the performance requirements to begin with.

For the purpose of project ZEAS the performance requirements of the future hydrogen-powered passenger ship, which meets the needs of Croatian shipowner Jadrolinija are presented in the following table.

Table 2 Ship performance and design requirements

Requirement	Input
Length	38 m (as per optimal design, no particular restriction)
Beam	(as per optimal design, no particular restriction)
Max. speed	13 kn (if possible to obtain with 1 MW power)
Cruise speed	11 kn
Approx. percentage of operational time traveling at max. speed	10%
Approx. percentage of operational time traveling at cruise speed	80%
Approx. percentage of operational time traveling at minimum speed	10%
Approx. time needed to embark and disembark all passengers	0,5 h
Range in M with one refill	min. 100 NM
Max time for 100% of refuelling	6 h (during the night, if the tank capacity is sufficient for completion of daily service with one charge)
Preferable line number where the ship is supposed to operate	Line 409 / alternatively 310, 505, 807
Sea state on the preferable lines	0 - 4 (acc. WMO Code Table 3700 - Moderate, Height 1,25 - 2,5 m)

Max. number of passengers	250 (winter/closed space)
Max. cargo weight	1,5 m^3 for cargo (approx. 2 t)
Cargo type	General, bulk
Hull type	Monohull
Hull material	Steel
Max. number of the crew	6
Min. number of the crew	4

The ship’s hydrogen technical-technological solutions are assessed in the aspect of suitability to the presented performance and design criteria.

Passenger safety is paramount in ship design and operation. The referent passenger ship must be designed in accordance with international regulations, rules and regulations of a selected classification society and the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code).

The initial premise is that the passengers should be kept as far as possible from the pressurized hydrogen tanks and fuel cells, during navigation, boarding and disembarking. The IGF provides detailed rules about ship design, fuel systems, pipe design, fire safety, explosion prevention, and others.

Because of everything mentioned above the HFCs system's physical location onboard is crucial. Areas where high-pressure hydrogen storage tanks, fuel processing units, and the HFCs train itself are placed should be during the design of the ship prioritized for safety.

On passenger ships of similar sizes, the preferred locations for passenger areas and communication routes are forward or aft deck, i.e. areas that typically offer ample space for passenger queuing and directing to the gangway. However, the ship’s mid-section can be used as well.

Figure 1 HFC propelled ship „Sea Change“ with an access point in the bow section

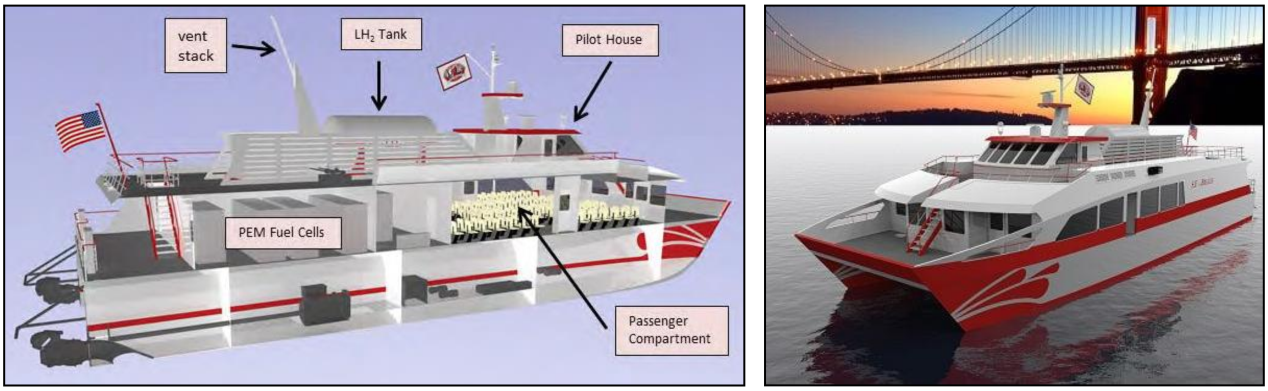

Figure 2 Project of HFC-propelled ship „SF-Breeze“ with access point in mid-section

Maintaining a safe distance from high-pressure hydrogen storage and other HFC components minimizes potential risks in case of unforeseen circumstances. The chosen location should ensure unobstructed access to life rafts, muster stations and emergency exits.

Prioritizing safe passenger communication routes and areas while maintaining a safe distance from the HFC system and emergency equipment is mandatory. In general, since the HFC system components are supposed to be placed mainly in the stern section of the ship’s hull, it is recommended to consider placing communication routes and areas in the mid-ship section or on the fore deck.

4.2 Hydrogen Fuel Cell types

Hydrogen fuel cells (HFCs) are sources of electrical power in which the chemical energy of a fuel cell is converted directly into electrical and thermal energy by electrochemical oxidation (MSC.1/Circ.1647) i.e. a system that directly converts hydrogen and oxygen into electricity, producing only water vapor as a by-product. However, understanding the basic technical features, advantages and drawbacks of different fuel cell types and their suitability for specific applications is crucial to propose the most suitable option for the referent ship.

The most prominent fuel cell types developed until now include[1]:

- Polymer Electrolyte Membrane Fuel Cells (PEMFCs)
- Direct Methanol Fuel Cells (DMFCs)
- Alkaline Fuel Cells (AFCs)
- Phosphoric Acid Fuel Cells (PAFCs)
- Molten Carbonate Fuel Cells (MCFCs)
- Solid Oxide Fuel Cells (SOFCs).

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[1] American Bureau of Shipping, Guide for fuel cell power systems for marine and offshore applications, 2019.

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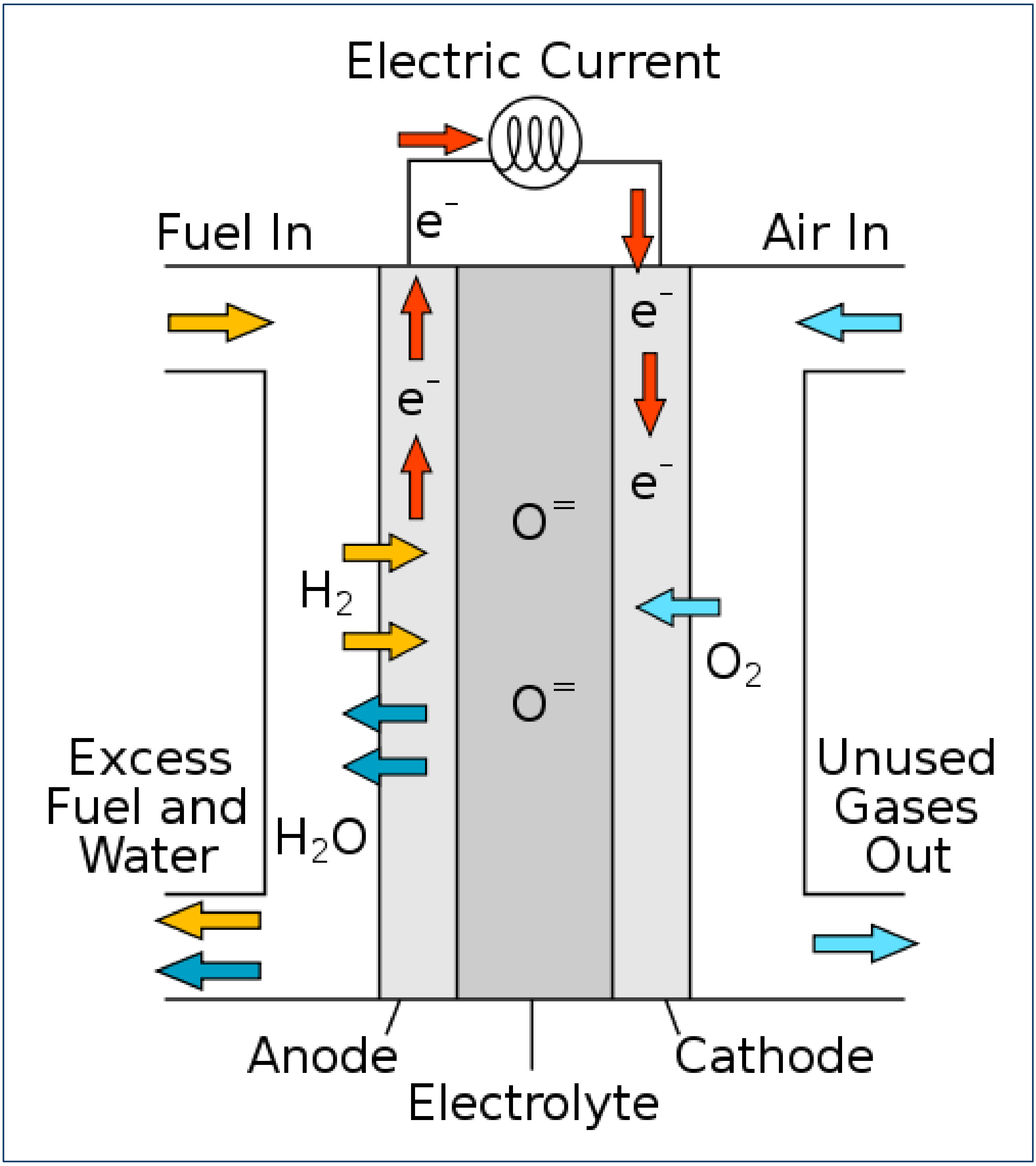

Figure 3 Fuel cell

Polymer Electrolyte Membrane Fuel Cells (PEMFC):

- Features: The system is also called Proton Exchange Membrane (PEM). PEMFCs utilize a solid polymer membrane as the electrolyte and porous carbon electrodes containing a platinum or platinum alloy catalyst. It needs hydrogen, oxygen and water to operate. The system operates at low temperatures (approx. 80°C, but can vary 50-120°C) allowing them to start in less time compared to other systems. Their compact size and quick start-up make them ideal for portable applications and vehicles i.e. transport sector. The electrical efficiency of these systems is approximately 60%. They can be used on ships in the power range of 30-50 kW. This type of fuel cell has a high power-to-weight ratio (100-1.000 W/kg), low working temperature, which enables flexible work and less demanding materials. The maximum power is up to 120 kW, they are small in size and therefore suitable for use in the shipping industry.

- Advantages: high power density and low weight and volume compared to other systems; fast response to changing power demands; low emissions; less wear and high durability; short warm-up time and relatively mature technology already applied in the transport sector.
- Disadvantages: cost, since requires a noble metal catalyst (usually platinum); sensitivity to impurities in hydrogen fuel; sensitivity to carbon monoxide accumulation; it requires humidification and has limited tolerance to high temperatures.

Direct Methanol Fuel Cells (DMFC):

- Features: Similar to PEMFCs but it uses liquid methanol as the fuel. The hydrogen is generated within the fuel cell from the methanol mixed with water. In general, the system offers higher energy density and easier fuel storage. Widely used in portable electronics and auxiliary power units. The electrical efficiency of these systems is approximately 40%.
- Advantages: simpler fuel handling (transport and supply in liquid form); higher theoretical energy density, and lower operating temperature than PEMFCs.
- Disadvantages: lower efficiency compared to PEMFCs, and methanol poses environmental concerns.

Alkaline Fuel Cells (AFC):

- Features: AFCs utilize a potassium hydroxide solution as the electrolyte and different non-precious metals as a catalyst at the anode and cathode. New AFCs use a polymer membrane as the electrolyte. In general, the system operates at moderate temperatures (60-100°C). They are considerably susceptible to CO_2 accumulation which can significantly affect the performance and durability due to carbonate formation. The fuel can be pure hydrogen or methanol. These mature and durable cells are often employed in stationary power applications and have been used in space applications. The electrical efficiency of these systems is approximately 60%.
- Advantages: mature technology; lower manufacturing cost than PEMFCs and relatively tolerant to fuel impurities.
- Disadvantages: Lower power density; operation at higher temperature, sensitivity to carbonate formation; slower response time; requires a liquid electrolyte; hindering portability; lower performance and durability compared to PEMFC.

Phosphoric Acid Fuel Cells (PAFC):

- Features: PAFCs utilize phosphoric acid as an electrolyte contained in Teflon-bonded silicon carbide matrix and porous carbon electrodes containing a platinum catalyst. The system operates at high temperatures (150-200°C). The fuel is pure hydrogen. The PAFC is a mature fuel cell type, with higher efficiency and tolerance for impurities it is suitable for stationary power generation and transportation applications. PAFCs are more than 85% efficient when used for the co-generation of electricity and heat but they are less efficient at generating just electricity (37%–42%).
- Advantages**:** High efficiency; tolerant to fuel impurities; relatively long lifespan.
- Disadvantages: cost due to expensive platinum catalyst; slower start-up time; large size and weight; less power compared to other systems given the same weight and volume; requires cooling systems; impacting portability.

Molten Carbonate Fuel Cells (MCFC):

- Features: MCFCs utilize a molten carbonate mixture as the electrolyte suspended in a porous, chemically inert ceramic lithium aluminium oxide matrix. Non-precious metals can be used as catalysts at the anode and cathode. The system operates at very high temperatures (600-800°C). These high-efficiency cells find application in large-scale stationary power generation. Unlike AFC and PAFC fuel cells, MCFCs do not require an external reformer to convert fuels such as natural gas and biogas to hydrogen. At high operating temperatures methane and other light hydrocarbons in these fuels are converted to hydrogen within the fuel cell itself (internal reforming) reducing cost. The electrical efficiency of these systems is approximately 50%.
- Advantages: high efficiency; fuel flexibility; ability to utilize low-grade heat sources for cogeneration.
- Disadvantages: complex design; long start-up time; requires stringent safety measures due to high operating temperatures; limited durability (app. 5 years); corrosion; limited scalability to smaller applications.

Solid Oxide Fuel Cells (SOFC):

- Features: SOFCs utilize a solid ceramic compound as the electrolyte. The system operates at high temperatures (700-1.000°C). Due to high-temperature operation the system doesn't needs noble metal catalyst which reduces cost. SOFCs reforms fuel internally, enabling the use of a variety of fuels (natural gas, biogas, etc). This fuel flexibility and high efficiency make them attractive for distributed power generation and transportation applications. SOFCs are approximately 60% efficient at converting fuel to electricity. In co-generation applications (utilizing heat), overall fuel use efficiency increases to 85%.
- Advantages: high efficiency; fuel flexibility; sulphur and carbon-monoxide resistant; low emissions; suitable for large fixed installations.
- Disadvantages: very high operating temperatures require complex thermal management systems; long start-up time; low durability; still under development for smaller applications.

Understanding the intricate details of each hydrogen fuel cell type is crucial for selecting the optimal solution for specific needs. Each technology offers advantages and disadvantages, necessitating consideration of application requirements, fuel availability, efficiency goals, and cost constraints. As fuel cell technology continues to evolve, advancements in materials, design, and manufacturing promise to further enhance their performance and affordability, solidifying their role in a sustainable future. It is worth mentioning that the HFC system requires an external air intake or exhaust vent, the gangway's position should be placed at a safe distance and not interfere with the proper airflow.

Determining the most feasible hydrogen fuel cell type for a rather small passenger ship requires careful consideration of various factors. The key considerations for choosing a fuel cell type may include:

- Application suitability: fuel cell system capable of delivering the power requirement (higher power density); small system size suitable for transportation application i.e. the referent ship.
- Maturity: the system should be commercially available for the transportation sector with acceptable design complexity which can meet the ship’s safety standards.
- Fuel availability**:** the system that utilizes the type of fuel readily available on the market; the ship’s system must be refuelled safely and efficiently not impairing the regular ship’s operation.
- Efficiency**:** the system should be efficient as much as possible in generating electrical power.
- Cost**:** the Capex and Opex should be as low as possible in a way that the investment in the ship’s operation is feasible.

Table 3 Fuel cell types key features

Fuel cell	**Application suitability**	**Maturity**	**Fuel**	**Efficiency**	**Cost (mutual comparison)**
PEMFC	Yes - higher power density - fast response - compact size	Yes	Pure hydrogen	~ 60%	Relatively affordable
DMFC	Yes - higher power density - compact size	Yes	Methanol	~ 40%	Relatively affordable
AFC	Partially - low power density - slower response time - tolerant to impurities	Yes	Hydrogen or methanol	~ 60%	Relatively affordable
PAFC	No - low power density - slower response time - large size and heavy	Yes	Pure hydrogen	~ 40%	Higher costs (materials)
MCFC	No - slower response time - large size and heavy - limited durability	Partially	Fuel flexible (gas/liquid)	~ 50%	Higher costs (complex designs and materials)
SOFC	No - slower response time - large size and heavy - limited durability	Partially	Fuel flexible (liquid)	~ 60%	Higher costs (complex designs and materials)

According to the DNV-GL, the most suitable fuel cells for marine use are fuel cells with solid oxides as an electrolyte, fuel cells with a polymer membrane as an electrolyte, and high-temperature fuel cells with a polymer membrane as an electrolyte.

According to the presented features, currently, **PEMFC type fuel cell type is the most viable option** for smaller passenger ships due to their maturity, compactness, fast response, acceptable efficiency and relatively lower cost compared to other systems.

4.3 Battery system

While hydrogen fuel cells (HFCs) offer a clean and efficient path toward sustainable ship propulsion, the inclusion of batteries presents a technical debate in the available literature. In this chapter the necessity, potential benefits and drawbacks of batteries in conjunction with HFCs are presented.

In general, for ships propelled by electrical systems, the overall electrical demand may be divided into two categories:

- the ship's propulsion and
- auxiliary systems (all other ship's systems that need power during navigation and stay in port).

Regarding propulsion, batteries are not strictly necessary for the core functionality of HFC propulsion, which may be utilized as a sole source of DC electrical energy, but with certain limitations. The Auxiliary systems may be powered by the same HFCS system or by another power source. It should be mentioned that some HFC systems are slow in reaction and require batteries for peak load.

To address the limitations, a relation between power density and energy density of different energy sources is important. Power density refers to how quickly a device can discharge its energy, while energy density refers to how much energy a device contains. In general, batteries have higher power density but lower energy density in comparison to to fuel cells meaning they can provide less energy per L (volumetric power density) or kg (gravimetric power density), but that is discharged and becomes available quicker.

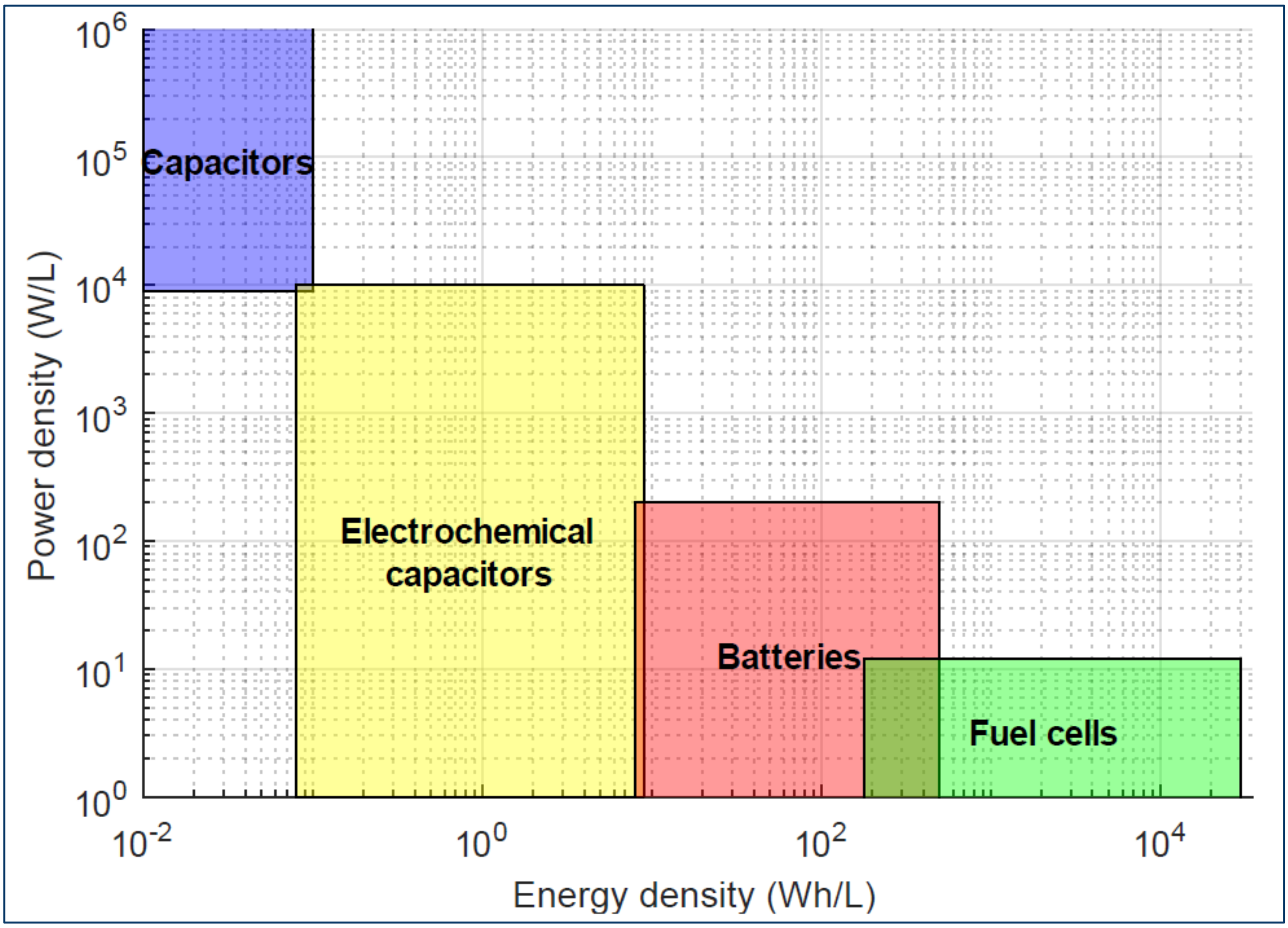

Figure 4 Power density and energy density of various power sources - Ragone plot

In that respect a hybrid system, combining HFCs and batteries, exploits the advantages of both systems: the flexibility of batteries in terms of power and the high energy density of HFCs.

Scenarios where batteries can complement HFCs:

- Power fluctuations: HFCs operate most efficiently at a constant load. Batteries can act as a buffer, absorbing excess power during peak generation and smoothing out fluctuations during high-demand periods.

- Manoeuvring and docking: during manoeuvres and docking, short bursts of high power are required. Batteries can provide this immediate surge, reducing strain on the HFCS system and optimizing fuel efficiency.
- Peak shaving and grid integration: in hybrid configurations, batteries can store excess energy generated during off-peak hours and provide power during peak demand periods, reducing reliance on shore power and potentially lowering operational costs.

Drawbacks of battery integration:

- Weight and space constraints: large battery banks add significant weight and occupy valuable space on ships, which may impact overall payload capacity and cargo space.
- Cost considerations: batteries are expensive compared to HFCS systems, increasing the initial investment, and potentially hindering widespread adoption.
- Limited charging infrastructure: reliable and readily available charging infrastructure for large-scale maritime applications is still in its early stages. However, an HFC system may be designed to charge the batteries during normal operational load i.e. during the ship's navigation.

Therefore, a smaller ship with frequent manoeuvring with high peak power demands (like the referent ship with its performance needs) might benefit more from batteries compared to a larger cargo ship which operates on longer distance routes, and with mainly steady-state operation.

The hybrid systems may be divided into:

- “HFCs dominant” and
- “HFCs range extender” solutions.

The HFCs dominant system is characterized by a minimum battery buffer with the following features:

- The HFCs must be able to meet the overall ship's consumption power (ship's propulsion and all accessories). This setup, to meet all power requirements, may lead to HFCs oversizing.
- Due to the constant matching of power generation and consumption, the HFC powertrain may be stressed with high load dynamics that might reduce the overall fuel cell lifetime.

HFC range extender system is characterized by an optimum battery buffer with the following features:

- The ship's operational range is increased due to a dual power source, a HFC and a battery system.

- During maneuvering the ship may rely on battery systems with no stress risk on the HFC system.
- The high battery capacity leads to a significant increase in capital costs.

While HFCs might operate alone without the immediate need for extensive battery banks, they can offer significant operational benefits in specific scenarios. Batteries are used to supply power during voltage sags and peaks, during manoeuvring, and to provide general stability to the electrical system. Batteries can be used as a power source during emergencies, they may be designed to provide enough power to run a propulsion system for a while, and they will be able to run navigation, communication and ship's emergency systems as required by class society technical rules and regulations.

During the ship's design phase, it is highly recommended to simulate the overall ship's power consumption (propulsion and all auxiliary systems) during navigation, manoeuvring and ship's stay in port to calculate the optimal battery capacity for the referent ship.

4.4 H2 Engines technology

Hydrogen shows promise as a fuel for internal combustion engines (ICEs) and fuel cell (FC) vehicles, with ICEs offering advantages like contamination tolerance and easy adaptation. The main potential pollutant from hydrogen combustion is nitrogen oxides (NOx), but advanced combustion processes can reduce emissions to near zero. Despite its benefits, hydrogen's low density compared to natural gas poses challenges, affecting power output. Direct H2 injection and increased storage pressure can mitigate this issue. Hydrogen's high diffusivity and flame speed improve combustion efficiency, allowing for lean mixtures and reduced NOx emissions. However, challenges like lubricant evaporation and particle formation in direct injection engines persist. Overall, hydrogen's properties offer opportunities and challenges for its use as an engine fuel. Hydrogen can be used in internal combustion engines (ICEs) in two different main engine groups and subdivided into additional subgroups:

- Spark ignition engine (SI),
  - Manifold induction - Low-temperature hydrogen is injected into the manifold through a valve-controlled duct.
  - Direct introduction - A cryogenic cylinder is used to store hydrogen. A pump circulates liquid hydrogen to a heat exchanger to vaporize it. Then, cold hydrogen is injected into the engine. By using cold hydrogen, pre-ignition is avoided and NOx formation in the combustion process is reduced.
  - Hydrogen addition to gasoline: In this method, a mixture of hydrogen and petrol is introduced into the combustion chamber of an internal combustion engine. There, the compressed mixture is ignited by a spark.
- Compression ignition (CI) engine.

Spark ignition engines can be fuelled with hydrogen without requiring major modifications. A higher hydrogen burning velocity improves combustion and allows for higher brake thermal efficiency. Emissions of hydrocarbons and carbon monoxide are virtually negligible. Only trace amounts of these emissions are produced by the evaporation and burning of the lubricating oil film on engine cylinder walls.

In hydrogen-fuelled compression ignition (CI) engines, the injector plays a crucial role in injecting high-pressure hydrogen into the cylinder, dictating how pressurized hydrogen enters the combustion chamber. As CI engines alone cannot ignite hydrogen due to its high autoignition temperature, combustion necessitates the assistance of a spark plug or a glow plug. In dual-fuel engines, hydrogen serves as the primary fuel injected into the intake air, while diesel acts as the ignition source. Typically, the pilot fuel constitutes 10-30% of the total fuel, with hydrogen providing most of the energy. Analogous to spark ignition engines, nitrogen oxides (NOx) pose a significant challenge in hydrogen-fuelled dual-fuel CI engines.

In general, hydrogen engines are prone to some operational challenges as knocking, preignition effects and backfiring to the inlet manifold. Some challenges related to hydrogen fuel injection are hydrogen fugacity, material compatibility and cost of compression equipment. Shorter quenching distances mean increased heat wall transfer. Otto process in hydrogen engines is less likely to be introduced due to challenging combustion control and high engine derating compared to the diesel process.

4.4.1 Current development status of H2 engines for ship propulsion

Some various concepts of hydrogen engine technologies that are in the testing phases are presented as follows.

- MAN Diesel: The current spark ignition diesel engines used with LNG fuel can only achieve 50% power when operating at 100% hydrogen concentration. These engines are primarily designed for stationary plants and are not suitable for marine applications due to their inability to effectively utilize hydrogen. In the marine industry, there are two main concepts for hydrogen engines: dual-fuel engines and compression ignition engines. Dual-fuel engines, which are already available on the market, have the capability to run on a maximum of 25% hydrogen while achieving full power only with liquid fuel. Despite being in the testing phase, these engines offer potential for marine use. On the other hand, compression ignition (CI) engines, which utilize the full potential of hydrogen as a fuel, are still under development and testing. Based on the diesel principle, these engines will operate solely on hydrogen with a fraction of pilot oil. It is expected that a dual-fuel engine capable of running on 100% hydrogen will be available within the next few years. However, their availability on the market will depend on further development and market demand.
- MAN Truck and Bus: In May 2022, MAN Engines put its first two dual-fuel hydrogen-powered engines for workboats into serial operation. These comprise two twelve-cylinder diesel engines of type MAN D2862 LE448, each with an output of 749 kW (1019 hp) at 2100 rpm. The engines are IMO Tier III-certified and equipped with a Selective Catalytic Reduction exhaust gas aftertreatment system. Both V12 engines have been prepared for dual fuel operation by MAN Engines and supplemented with a hydrogen injection system by development partner CMB.TECH. The low-emission engine is used on the world’s first hydrogen-powered crew transfer ship (CTV), the “Hydrocat 48” from Windcat Workboats.

Figure 5 Hydrogen engine onboard powered windcat workboat by MAN (photo: mantruckandbus.com)

- Rolls Royce (MTU): Rolls-Royce has reached the successful testing of a 12-cylinder gas variant of the MTU Series 4000 L64 engine, running entirely on 100% hydrogen fuel in 2023. These tests, conducted by the Power Systems business unit, have showcased highly favourable characteristics in terms of efficiency, performance, emissions, and combustion. Presently, gensets powered by MTU Series 500 and Series 4000 gas engines can operate with a gas blending of up to the threshold of 25%. Furthermore, conversion kits will be offered for already installed gas engines in the field, enabling them to operate on 100% hydrogen and facilitating the transition to cleaner energy sources.

  On April 2024 the MTU stated that cannot offer certified engines running on hydrogen or hydrogen blend that can be installed onboard a ship.

- Wärtsilä**:** In October 2022, Wärtsilä and WEC Energy Group conducted successful tests at WEC Energy Group's A.J. Mihm power plant in Michigan, USA, demonstrating an unmodified Wärtsilä 50SG engine running on a 25 vol% hydrogen-blended fuel, a world-first achievement. The Electric Power Research Institute (EPRI) confirmed the feasibility of blending hydrogen with natural gas for existing Wärtsilä engines in a recent report, highlighting improved efficiency and reduced greenhouse gas emissions. During continuous testing, the engine showed efficiency gains and maintained compliance with emissions regulations, achieving a 95% engine load with the 25 vol% H2 blends. EPRI's analysis suggests that these engines can outperform simple-cycle gas turbines in efficiency and lower CO2 emissions relative to turbines. The tests, conducted in collaboration with WEC Energy Group and EPRI, demonstrate the adaptability of the Wärtsilä 50SG engine to hydrogen-based power generation. With its capability to efficiently co-fire hydrogen blends while maintaining compliance with emissions standards, the Wärtsilä 50SG engine proves to be a promising solution for potential marine applications.

- Cummins: Cummins embarked on hydrogen internal combustion (ICE) technology testing in July 2021, with early results surpassing production power and torque targets, achieving over 1098 Nm torque and 290 hp from the medium-duty engine. Further testing on advanced prototypes is slated to commence soon, as Cummins plans to develop hydrogen internal combustion engines in both 15-liter and 6.7-liter displacements. The company sees these engines as pivotal in addressing greenhouse gas (GHG) emissions and accelerating carbon reduction efforts within this decade. In a significant move in 2022, Cummins unveiled its 15-liter hydrogen engine at ACT Expo in Long Beach, California. This engine is part of Cummins' fuel-agnostic platform, wherein components below the head gasket are largely similar across different fuel types, while those above are tailored for specific fuels. With full production expected by 2027, this hydrogen engine is designed to operate on clean, zero-carbon hydrogen fuel.

- Caterpillar: Caterpillar’s line-up of gas generator sets is capable of operating on natural gas blended with up to 25% hydrogen by volume including power generators from 600 kW to 2.5 MW for 50 or 60 Hz continuous, prime, and load management applications. These include Cat CG132B and Cat CG170B generator sets as well as the G3500H series platform. Additionally, the company offers aftermarket retrofit kits for updating these models to provide the same hydrogen blending capabilities of up to 25% hydrogen by volume. Since 2022 Caterpillar has offered demonstrator generating set G3516 capable of running on 100% hydrogen, with a maximum rating of 1250 kW for 50 Hz and 60 Hz continuous applications.

  On Apr. 2024 Caterpillar stated that cannot offer certified engines running on hydrogen or hydrogen blends that can be installed onboard a ship.

Therefore, as a general ruler currently, hydrogen engines for marine propulsion are still in the development stage. Hydrogen engines are still further away from industry introduction. Although the fast time to market is expected to be achieved in the first phase of engine introduction due to the possibility of present platform utilizations, some performance compromises will therefore have to be accepted, especially in the power density field. Furthermore, the second hydrogen engine phase introduction will feature an engine design dedicated specifically to hydrogen where higher engine performances are expected to be achieved, which might be equal to present liquid fuel engines. The present hydrogen engine development stage is the main reason that engines cannot be used for the propulsion of the present ship and therefore fuel cell technology is the feasible and available solution for ZEAS project. The only exception present engine is MAN D2862 LE448 which is currently installed onboard a ship but this engine operates on both classical diesel fuel and hydrogen mixture and therefore does not present a zero-emission solution for ship propulsion.

4.4.2 Cost comparison

As already presented hydrogen engine's development stage is the main reason that still cannot be used for the propulsion of the present ship. However, MAN D2862 LE448 engine on dual fuel is installed onboard a ship used for ship propulsion**.**

Basic fuel and emission savings analysis is performed based on power generated for propulsion purposes. The estimated propulsion power needed for the model ship is taken as an average 730 kW - 750 kW. That power is estimated based on ZEAS design requirements and projected between model ship “Unije” (LOA 46 m, speed 12,5 kn, power 1.268 kW) and model ship “Lara” (LOA 36 m, speed 12 kn, power 530 kW). This also corresponds to model engine D2862 LE448 power and is equivalent to 2 units of fuel cell TACO FCM 400.

Table 4 Fuel consumption comparison (H2 engine vs Fuel Cell)

	MAN D2862 LE448 dual fuel			**TECO FCM 400**
	Dual fuel engine (diesel/hydrogen)			**Proton exchange membrane fuel cell**
Rated power	749 kW			2 x 366 kW
Eco load power	600 kW			No available data
Fuel consumption @ rated power	Pure diesel mode	Dual fuel mode (diesel + hydr)		2 x 20,5 kg/hr Hydrogen
	180 ltr/hr	148 ltr/hr	12 kg/hr Hydr	
Calculated fuel cons. during sailing (1 hr) - rated power - 100% load	180 ltr/hr	148 ltr/hr	12 kg/hr	41 kg/hr
Calculated fuel cons. during sailing (1 hr) - propeller curve - eco load *	140 ltr/hr	90 ltr/hr	16 kg/hr	No available data
Fuel price **	1,9 €/ltr	1,9 €/ltr	5 / 9 €/kg	5 / 9 €/kg
Fuel cost (total per 1 hr) - rated power	342 €	341 for 5€/kg H_2 389 € for 9€/kg H_2		200 for 5€/kg H_2 369 € for 9€/kg H_2
Fuel cost (total per 1 hr) - eco power	266 €	251 for 5€/kg H_2 315 € for 9€/kg H_2		No available data
Emission reduction (savings)***	No reduction	Rated power - 93 kgCO_2/hr Eco power - 119 kgCO_2/hr		No CO_2 emission

* Engine eco load is based on propeller curve and estimated to operate at 1900 rpm - with appropriate mixture rations between diesel/hydrogen

** Fuel prices are taken as average; Diesel - INA Eurodiesel retail price € 1,9/ltr; Hydrogen Valley external sales prices in EU - average most common suppliers' prices - 5 €/kg and 9 €/kg

*** Tank to wake methodology, IMO emission factors C_f = 3,206 gCO_2/g fuel (diesel fuel), Average density - 830 kg/m^3

Based on the fuel consumption analysis fuel cell presents more economical solutions, offering potential savings from 20€ - 141 € per hour during sailing at rated power. However, the potential economic benefits of using fuel cells rely greatly on the present hydrogen price on the market. In case the hydrogen market price exceeds 10 €/kg, the engine would present a more economical solution from this standpoint. Unfortunately, due to data unavailability, it was not possible to compare fuel cost savings at lower eco load.

Table 5 Fuel costs for different hydrogen price

Hydrogen price €/kg	**MAN D2862 (diesel mode)**	**MAN D2862 (diesel + hydrogen mode)**	**TACO FCM 400**
5 €	342 €/hr	341 €/hr	200 €/hr
7 €		365 €/hr	287 €/hr
8 €		377 €/hr	328 €/hr
9 €		389 €/hr	369 €/hr
10 €		401 €/hr	410 €/hr
11 €		413 €/hr	451 €/hr

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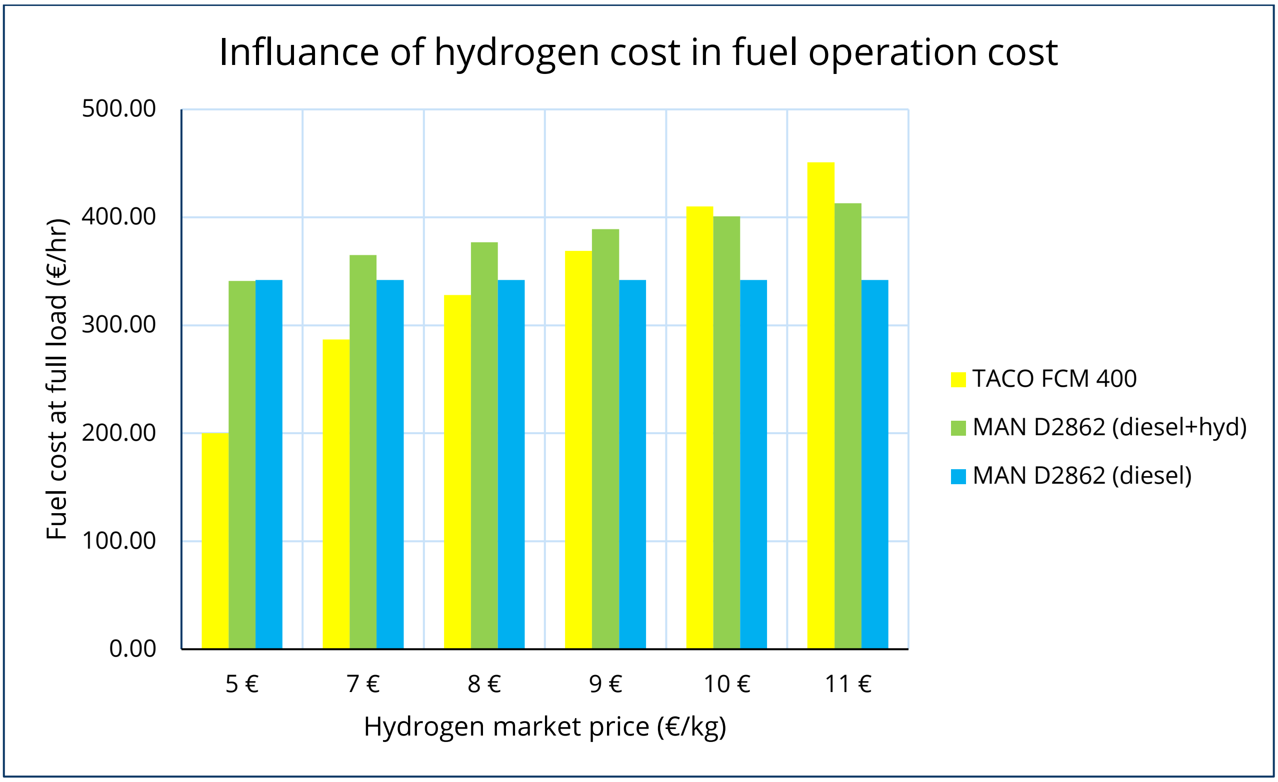


Figure 6 Influence of hydrogen cost in fuel operation cost

From an emission standpoint dual fuel engine still generate a significant amount of CO_2 emission, while fuel cell offers zero emission solutions if tank-to-wake methodology is considered. In the best-case engine solution would offer a maximum reduction of 119 $kgCO_2$/hr while running in eco load in diesel + hydrogen mode. In this case, engine would still generate 230 $kgCO_2$/hr, without taking into consideration other emissions (NO_x, PM, etc.). Therefore, a fuel cell solution is the only viable solution from an ecological standpoint and economic standpoint if the hydrogen market price is below approx. 9,5-10 €/kg. Furthermore, the H2 engine solution would be more viable only in case of very high hydrogen market prices or challenges in hydrogen supply in the market and associated supply chains.

4.5 Fuelling and storage facility

4.5.1 Storage

Storing hydrogen brings a certain risk level as it is non-toxic, colourless, odourless, tasteless and highly combustible. Additionally, hydrogen is extremely light and can diffuse through certain materials. All these yields important criteria to be observed in the design process of hydrogen storage facilities.

The primary safety requirements are:

- leak tightness of the storage facilities and
- high fatigue resistance.

Hydrogen is stored in tanks in either gaseous or liquid form.

According to the International Renewable Energy Agency (IRENA) liquefied hydrogen has a higher density than compressed hydrogen which enables more economical required instalment area (space) management. Higher density also implies higher volumetric energy density. The downside of liquified storage is the need for low temperatures in the storage facility, namely below minus 252,8 °C. The need for such low temperatures implies a significant reduction in energy efficiency as an estimated 30 to 40% of the hydrogen energy content is used for the liquefication process (compared to 15% in the case of compressed gas storage). Furthermore, the low temperatures needed to store and transport hydrogen require that all related mechanical elements such as valves or tanks resist hydrogen embrittlement. Ships transporting liquefied hydrogen either assume significant levels of evaporation due to the cold and lightness of the fluid or need to improve the insulation of the load or even invest in complex cryogenic systems.

Hydrogen can be stored using physical-based methods, such as:

- compressed hydrogen,
- cryogenic liquid hydrogen, and
- cryogenic compressed liquid hydrogen,

and material-based methods, including using:

- liquid chemical hydrogen carriers,
- metal hydrides, and
- adsorbents.

In maritime applications the available volume for hydrogen storage becomes somewhat limited so higher storage pressures are required to economize space utilization.

If hydrogen is compressed two pressure levels are used in the shipping industry, namely 350 and 700 bar. Five standardized tank types are used to store compressed hydrogen, namely Type I to V Hydrogen tank.

Type I tanks are made exclusively out of metal (steel or aluminium) with a metallic liner. This type of tank has no outer wrapping, the manufacturing process is relatively simple and consecutively low cost.

Type II tanks are constructed with a metallic liner (usually aluminium) with an outer composite material hoop wrapping for higher mechanical strength which opens the possibility for higher storage pressures. The wrap is relatively thin, so the total tank mass is not increased significantly.

In **Type III** tanks the metallic inner part no longer has a pressure load bearing role which is done by the outer composite material full wrapping.

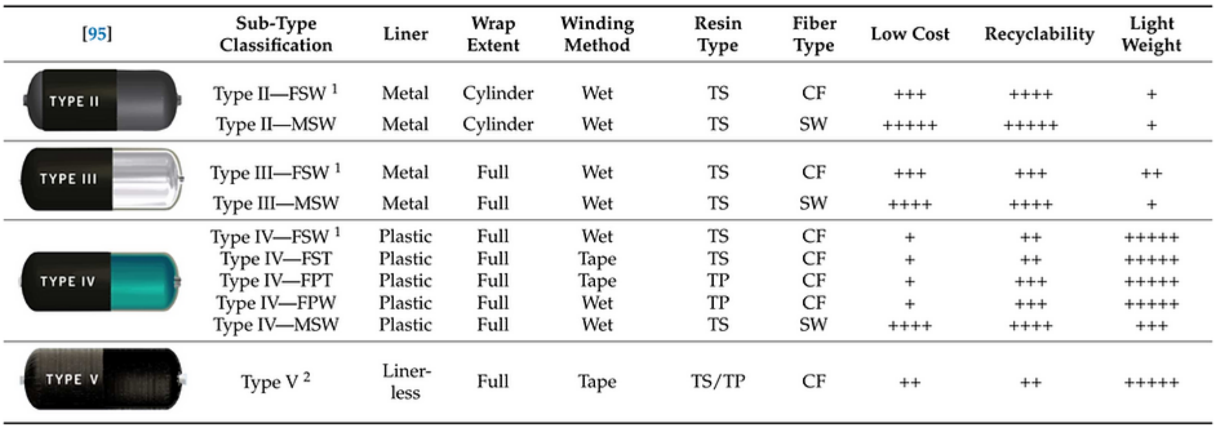
In **Type IV** tanks the liner metallic material is replaced by non-metallic materials in the effort to further reduce the tank mass.

The **Type V** tanks are completely made from composite materials.

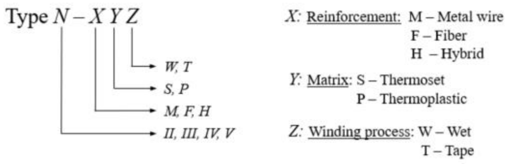
The most significant techno economical aspects for each type are summarized below:

- Type I: All-metal construction; steel or aluminium. Approximate maximum pressures: aluminium 175 bar (17.5 MPa; 2,540 psi), steel 200 bar (20 MPa; 2,900 psi). Approximate cost: 83 $/kg.
- Type II: Metal with fibre overwrap in the hoop direction, steel or aluminium with a glass, aramid, or carbon fibre wrap. Approximate maximum pressures: aluminium/glass 263 bar (26.3 MPa; 3,810 psi), steel/carbon or aramid 300 bar (30 MPa; 4,400 psi). Approximate cost: 86 $/kg.
- Type III: Tanks made from composite material, fiberglass/aramid or carbon fibre with a metal liner (aluminium or steel). Approximate maximum pressure: 700 bar (70 MPa; 10,000 psi). Approximate cost: 700 $/kg.
- Type IV: An all-composite construction, thermoplastic polymer, polyamide (PA) or high-density polyethylene (HDPE) liner with carbon fibre or hybrid carbon/glass fibre composite; the composite materials carry all the structural loads. Approximate maximum pressure: 700 bar (70 MPa; 10,000 psi). Approximate cost: 633 $/kg.
- Type V: All-composite, linerless tank. Approximate maximum pressure: 1,000 bar (100 MPa; 15,000 psi).

Table 6 Hydrogen Fuel Tank types (Source: https://www.addcomposites.com/post/what-is-a-hydrogen-tank-tank-types)



[95]	Sub-Type Classification	Liner	Wrap Extent	Winding Method	Resin Type	Fiber Type	Low Cost	Recyclability	Light Weight
TYPE II	Type II—FSW [1]	Metal	Cylinder	Wet	TS	CF	+++	++++	+
	Type II—MSW	Metal	Cylinder	Wet	TS	SW	+++++	+++++	+
TYPE III	Type III—FSW [1]	Metal	Full	Wet	TS	CF	+++	+++	++
	Type III—MSW	Metal	Full	Wet	TS	SW	++++	++++	+
TYPE IV	Type IV—FSW [1]	Plastic	Full	Wet	TS	CF	+	++	+++++
	Type IV—FST	Plastic	Full	Tape	TS	CF	+	++	+++++
	Type IV—FPT	Plastic	Full	Tape	TP	CF	+	+++	+++++
	Type IV—FPW	Plastic	Full	Wet	TP	CF	+	+++	+++++
	Type IV—MSW	Plastic	Full	Wet	TS	SW	++++	++++	+++
TYPE V	Type V [2]	Liner-less	Full	Tape	TS/TP	CF	++	++	+++++



Cryogenic liquid hydrogen (low pressure ~4 bar, low temperatures) and cryogenic compressed hydrogen (300 bar, near-ambient pressures) storage methods are also an option for maritime applications but negative aspects such as increased demands on thermal insulation, the current industrial capacity to produce liquid hydrogen being relatively low, specific design considerations to achieve cryogenic liquid hydrogen make these two options less appealing.

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Hydrogen on ships can be stored in gaseous form (compressed state), as a cryogenic liquid, in various chemical carriers (ammonia, methanol, MCH, DBT) or in metal hydrides (manganese, ferritic or lithium-based). The basic aspects and characteristics are summarized in the table below.

Table 7 Storage type for hydrogen (Source: Blue Economy, Hydrogen powering of ships, Phase I report, A review of the feasibility of utilising hydrogen as a marine fuel in Australia | November 2023)

Storage type	**State**	**H_2 density [kg/m^3]**	**Volumetric energy density [MJ/m^3]**	**Relative density**	**Storage density (wt%)**
Standard hydrogen	Gas	0.084	10.08	1	-
Compressed hydrogen	Gas	23 (350bar); 42 (700 bar)	2.760 (350bar); 5.040 (700 bar)	274 (350bar); 500 (700 bar)	5.5;7.7 (Type IV tank)
Cryogenic Liquid hydrogen	Liquid	65 (-237 °C, 4bar); 71 (-253°C)	7.800 (-237 °C, 4 bar); 8.520 (-253°C)	774 (-237 °C, bar); 845 (-253°C)	10
Cryogenic compressed hydrogen	Liquid	88 (-253 °C, 300 bar)	10,56 (-253 °C, 300 bar)	1.048 (-253 °C, 300 bar)	9
Liquid ammonia (Chemical carrier)	Liquid	121 (-33 °C)	14,520 (-33 °C)	1.440 (-33°C)	17.8
Methanol (Chemical carrier)	Liquid	99	11,880	1179	12.1

Hydrogen ship bunkering procedure in the case of compressed hydrogen, land-based refuelling technologies for vehicles can be used. Mobile compressed hydrogen bunkering method has been employed by the “Hydrocat 48” (CMB.TECH, 2022). Cryogenic liquid hydrogen is very similar to LNG, so bunkering can take place through shore-based station-to-ship, truck-to-ship, or ship-to-ship modes (Fan et al., 2021).

Power supply of compressor & cold-fill, onshore storage to decouple supply & refill, and flexibility to move refill equipment to the ship are important factors to consider during the decision process of choosing between a fixed charging station and a mobile (truck) station.

The decidedly simple way of transferring fuel to the ship is to use fixed shore-based systems in fixed ship tanks. In that case, the refill time is mainly limited by the maximum temperature of the tank material. The greater the pressure ramp rate, the higher the mass flow rates and the higher the hydrogen temperature in the tank will be. Cold fill allows faster refill but additional equipment necessary. On the assumption of the refilled amount needed of 400 kg in 5 hours starting at 10 bars up to 350 bar the average pressure ramp rate will be 1.13 bar/min and an average mass flow rate will be 80 kg/h. These values will consequently determine the size of the necessary equipment. It is noteworthy that faster refill rates in booster mode will lead to larger compressor, and therefore raise electrical power demand.

The required land space for a loading station depends on the plant layout itself. If the supply truck and trailer moving, parking required space it’s taken into consideration and a ground-level layout is adopted a 500 m^2 area is needed. The same is also valid for a mobile hydrogen distribution station (a truck) on a quayside (including a safety boundary to limit an unauthorized approach).

To fill the onshore storage facilities i.e. ship refuelling stations, hydrogen needs to be transported via road and rail transport systems. Shorter and medium-range transport is usually done on roads whilst long-distance international transportation utilizes rail.

All the parts of the transport systems for liquid hydrogen must be designed and manufactured to withstand low temperatures. An additional issue is ice formation on the equipment's surface. Since liquid hydrogen is non-corrosive no special material or actions to prevent corrosion are not necessary. The main considerations for materials used to handle liquid hydrogen include hydrogen embrittlement, permeability, and capability to withstand very low temperatures. Literature review indicates that liquid hydrogen road transportation can utilize trailers, which typically have a tank size of 30–60 m^3 that can hold 2.100–4.200 kg of hydrogen. For rail transport, a larger container of 115 m^3 (approximately 8.000 kg) can be utilized.

Thermal expansion of liquid hydrogen during transport limits the amount of filling during ship refuelling to approximately 85% of the ship volume. Transfer of liquid hydrogen should be performed in a vacuum-insulated system to minimize the loss due to vaporization and avoid the formation of liquid air with subsequent enrichment of oxygen.

The four main available onboard storage technologies are:

- Compressed: It is the most developed and well-experienced method. The hydrogen is kept under very high pressures around 350-700 bar which gives a density of 23.3 kg/m^3 and 39.3 kg/m^3, respectively (Raucci et al., 2015). The storage phenomena of compressed hydrogen have two main components: storage tanks, and compressors while on the proposed hydrogen ship compressor is not planned to be utilized.
- Liquid: The hydrogen is stored at the temperature to -253 °C which is its boiling temperature. The advantage of liquefaction is the ability to reach high hydrogen densities at atmospheric pressures, which is 70 kg/m^3 and 775 times higher than the gaseous form. The heat transfer must be minimized to keep the temperature at the desired level to store a cryogenic liquid. Like liquefied natural gas (LNG) transportation and boil-off gas use in marine diesel engines. Important issues for the liquid hydrogen are to minimize evaporation, pressure is increased inside the tank, there is a loss of the spent energy during the liquefication of the hydrogen and the reduction of heat transfer through the tank is the key solution to prevent evaporation.
- Solid-state: There are various methods to store hydrogen in solid materials. The most prominent ones are metal hydride (Mg) and boron-based storage ($NaBH_4$ and NH_3BH_3):
  - metal hydrides:
    - store hydrogen by chemically bonding the hydrogen to the metal,
    - hydrogen release by thermolysis or hydrolysis,
    - magnesium is widely available affordable and attractive hydrogen, storage density of 1.45 g/cm^3 and a high hydrogen storage capacity of 7.6% (wt.)
  - boron-based solid-state hydrogen:

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    - $NaBH_4$ and NH_3BH_3
    - both have >10% (wt.) hydrogen storage capacity
    - $NaBH_4$ with a hydrogen storage capacity of 10.8% (wt.) can be released from hydrogen at 530 °C
- Alternative carriers: ammonia, CO_2 based or organic liquids.

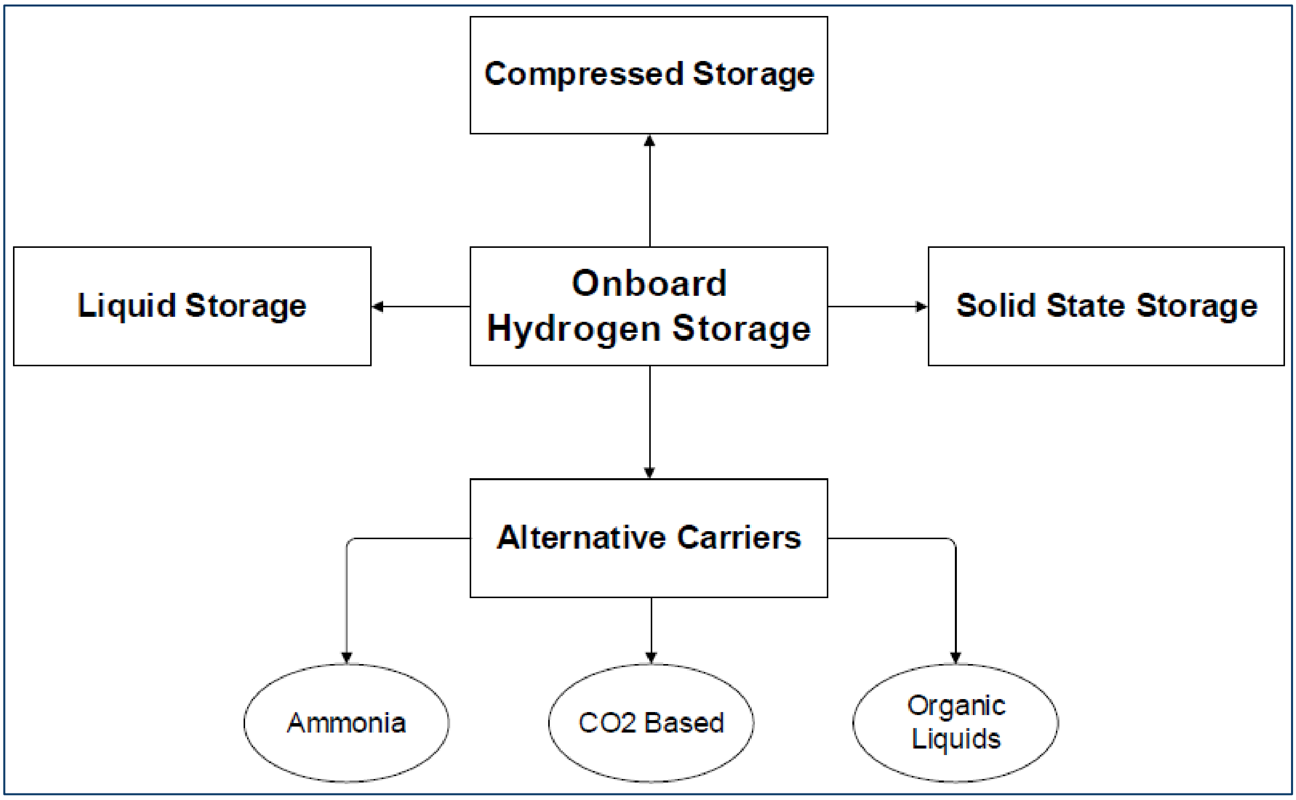

Figure 7 On-board hydrogen storage technologies (Source: Omer Berkehan Inal, Caglar Dere, Cengiz Deniz; Onboard Hydrogen Storage for Ships: An Overview, 5th International Hydrogen Technologies Congress (IHTEC-2021), May 26-28, 2021, Online):

The two hydrogen storage methods on ships that have proven the most suitable are compressed hydrogen and liquid hydrogen. The life span of the storage facilities coincides with the operational lifespan of ships.

The recommended choice of materials and design for fixed hydrogen tanks situated either inside the ship’s hull of outside (on deck) are tanks with outer wrapping made up of carbon fibre or composite material to withstand corrosion.

Pure hydrogen density is a function of pressure and temperature.

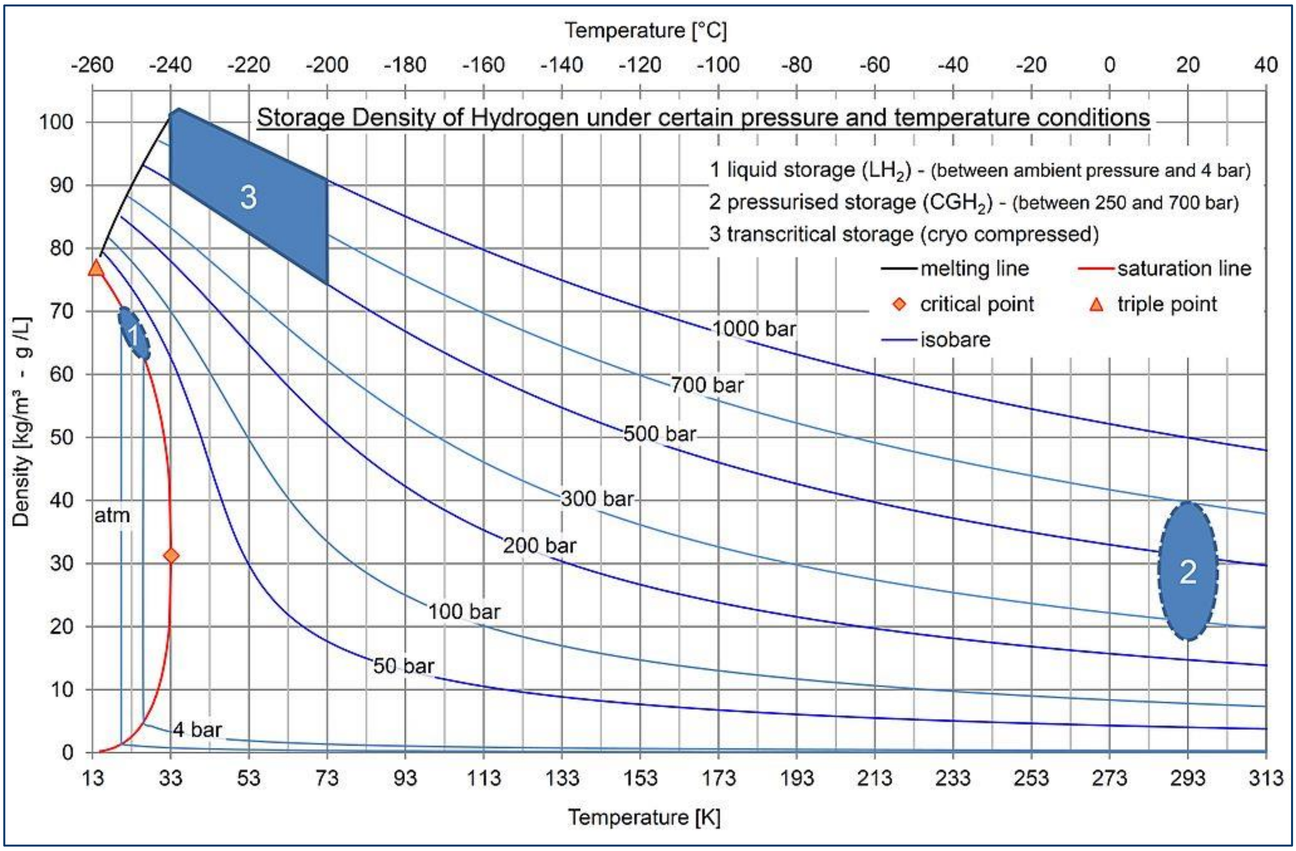

Figure 8 Hydrogen storage density under different pressure and temperature conditions (Source: https://en.m.wikipedia.org/wiki/File:Storage_Density_of_Hydrogen.jpg)

The suitable range for compressed hydrogen storage is between 250 and 750 bar at ambient temperatures (10 - 30°C).

The indicative weight (weight of tank divided by its volume) of different tank types are as follows (Source: R. Taccani et al. / High energy density storage for gaseous marine fuels, International Shipbuilding Progress 67 (2020) 33–56 33 DOI 10.3233/ISP-190274):

Type I:	0.9 to 1.3 kg/lit
Type II:	0.8 to 1.0 kg/lit
Type III:	0.4 to 0.5 kg/lit
Type IV and V:	0.3 to 0.4 kg/lit

For the ship foreseen by this project, the recommended size of hydrogen tanks will be designed for an estimated total capacity of 350 kg. Additionally, one tank solution is to be considered only if liquid hydrogen is used. In this case, the one tank solution allows to minimize the overall surface area and therefore the diffusion of hydrogen in the atmosphere.

Gaseous hydrogen requires several tanks to optimize space requirements and to offer the possibility of replacing single tanks presenting small cracks or any defects.

The storage assembly for the required 350 kg capacity at 300 bar and 20°C would require a total volume of approximately 17,5 m^3 as the hydrogen density for the given thermodynamic parameters is ~20 kg/m^3. The total mass of the tanks is expected to be:

- Type I: 16 to 23 t
- Type II: 14 to 18 t
- Type III: 7 to 9 t
- Type IV and V: 5 to 7 t

The final volume of the storage system should be defined after the filling dynamics will be defined to take into account the temperature reached by the hydrogen during the refilling process. Depending on the loading process, the hydrogen temperature could be higher than the ambient temperature. Therefore, the loaded hydrogen mass could be lower than expected.

Table 8 Onboard Hydrogen Storage for Ships Characteristics (Source: Onboard Hydrogen Storage for Ships: An Overview - Conference Paper, May 2021, authors: Omer Berkehan Inal, Caglar Dere, Cengiz Deniz, Istanbul Technical University)

Storage Technique	Safety	Applicability	Efficiency	Reliability	TOTAL
Compressed Hydrogen	++	++	+++	++	9
Liquid Hydrogen	+++	++	++	+++	10
Solid-State Hydrogen	+++	+	++	+++	9
Ammonia (N_2 Based) Storage	++	+++	++	+++	10
CO_2 Based Storage	++	+	+	++	6
Organic Liquid-Based Storage	+++	+	+	++	7

The table above shows the comparison of the advantages and disadvantages of the discussed options for hydrogen onboard storage. Regarding an additional characteristic of technological maturity, the option of compressed hydrogen stands out in comparison to other methods.

Adequate position of the hydrogen tanks on board a ship ("International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels") is on the top deck and astern close to the FCS.

4.6 Cost of ownership

The total cost of ownership (TCO) is the key factor in determining the feasibility of a hydrogen-powered ship. Three aspects to evaluate this cost are capital expenditure (CAPEX), operational expenditure (OPEX), and carbon benefits. The main upfront costs for hydrogen fuel cell-powered ships include hydrogen storage equipment, fuel cell systems (including stacks and related Balance of Plant systems), and batteries. The cost estimates can be derived from land-based equipment or systems. It's crucial to understand that the investment required for marine equipment and systems is significantly higher compared to similar land-based products. This is mainly because of the need to meet strict maritime environmental regulations (like vibration resistance and durability in high-salinity conditions) and secure certification from classification societies.

Projections indicate that the costs of hydrogen production from renewable sources are expected to decrease, primarily driven by the declining costs of wind and solar power, as well as advancements in water electrolysers.

5 CASE STUDIES FOR PASSENGER LINES

For the ZEAS project, Jadrolinija as one of the Consortium partners would use the ship to operate at 4 existing national lines and those were taken into consideration as a case (solution) to be elaborated. Currently, small passenger ships are engaged on all four lines and they are operating in the national waters of Croatia under the Croatian flag and classified under the Croatian Register of Shipping.

Jadrolinija has created design requirements for the development of hydrogen-fuelled ship based on the specifics of each line such as geographical area, transport passengers' demand, but also on the requirements stated in the Croatian Government decision "*The Decision on the Establishment of State Lines*" (Official Gazette 150/23).

Passenger lines are elaborated as follows:

- Zadar – Preko
- Mali Lošinj – Vele Srakane – Unije – Susak
- Vodice – Prvić Šepurine – Prvić Luka – Zlarin – Šibenik
- Suđurađ (Šipan) – Lopud – Koločep - Dubrovnik

The aforementioned lines were taken as appropriate lines following the project proposal that the ship will be approximately 38 m long with a target capacity of 250 passengers.

The minimum frequency of traffic and the minimum passenger capacity of the ship are described as follows (Official Gazette 150/23):

*Table 9 Minimum requirements (*The Decision on the Establishment of State Lines" - Official Gazette 150/23*)*

No.	Shipping line	Weekly return voyages			Min. passenger capacity
		Off-season	Low season	High season	
310	Mali Lošinj – Vele Srakane – Unije - Susak	13	13	13	200
409	Zadar – Preko	56	63	70	250
505	Vodice – Prvić Šepurine – Prvić Luka – Zlarin - Šibenik	32	33	33	300
807	Suđurađ (Šipan) – Lopud – Koločep - Dubrovnik	26	26	28	300

* 100 passengers in Off-season period

As previously presented the preliminary ship performance has been analysed by Jadrolinija taking into consideration existing data and specific passenger line requirements.

Table 10 Ship performance and design requirements

Requirement	**Input**
Length	38 m (as per optimal design, no particular restriction)
Beam	(as per optimal design, no particular restriction)
Max. speed	13 kn (if possible to obtain with 1 MW power)
Cruise speed	11 kn
Approx. percentage of operational time traveling at max. speed	10%
Approx. percentage of operational time traveling at cruise speed	80%
Approx. percentage of operational time traveling at minimum speed	10%
Approx. time needed to embark and disembark all passengers	0,5 h
Range in M with one refill	min. 100 NM
Max time for 100% of refueling	6 h (during the night, if the tank capacity is sufficient for completion of daily service with one charge)
Preferable line number where the ship is supposed to operate	Line 409 / alternatively 310, 505, 807
Sea state on the preferable lines	0 - 4 (acc. WMO Code Table 3700 - Moderate, Height 1,25 - 2,5 m)
Max. number of passengers	250 (winter/closed space)
Max. cargo weight	1,5 m^3 for cargo (approx. 2 t)
Cargo type	General, bulk
Hull type	Monohull
Hull material	Steel
Max. number of the crew	6
Min. number of the crew	4

5.1 Passenger line Zadar - Preko

Passenger line Zadar – Preko connects town of Zadar with the port Preko at the neighbouring island Ugljan. Line is numbered as line 409.

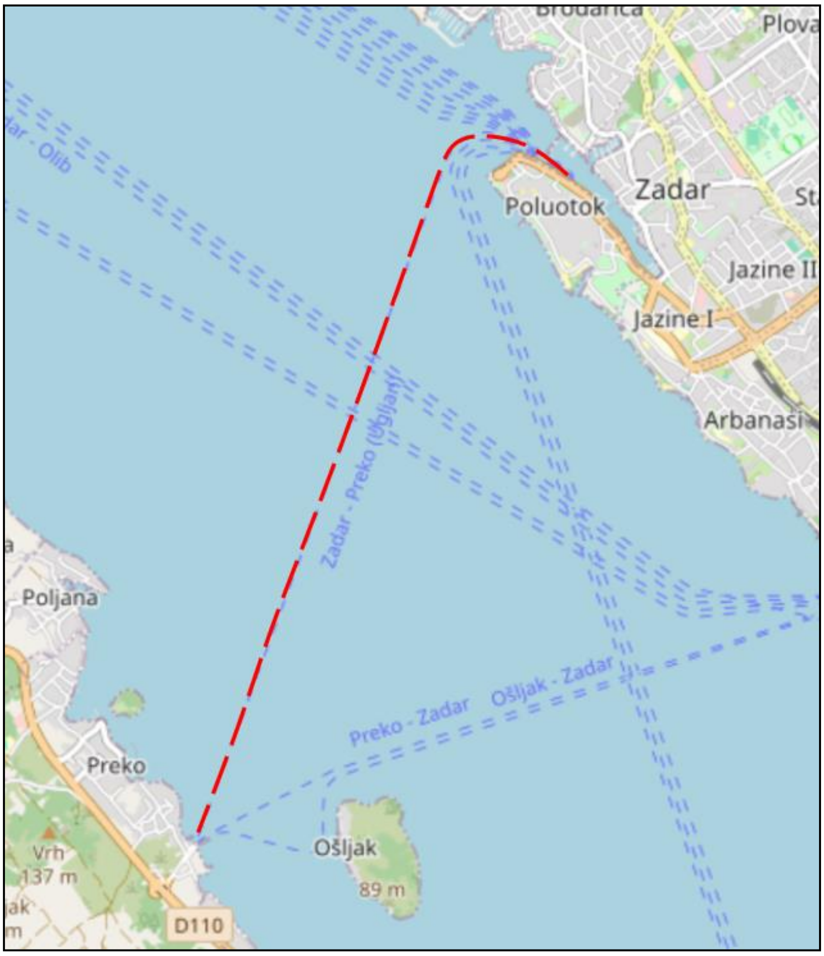

Figure 9 Passenger line 409 – Navigation route

The distance between ports is 3,3 M and the sailing time is 26 minutes. The values of speed, distance between ports and time of voyage are as follows:

Table 11 Characteristics of the passenger line (existing ship)

Ship status	Speed [kn]	Distance [NM]	Time [min]
Unberthing (Zadar)	-	-	1
Manoeuvring Zadar (manoeuvring speed)	5,5	0,7	7
Sailing (maximum speed)	10,0	2,5	15
Manoeuvring Preko (manoeuvring speed)	6	0,2	2
Berthing (Preko)	-	-	1
TOTAL		**3,3**	**26**

Currently, on passenger line 409 Zadar - Preko, the passenger ship “Dora” operates with the following characteristics:

Table 12 Passenger ship “Dora”

Ship type	**Passenger ship**
IMO No.	8904290
MMSI	238110140
Callsign	9A2184
Flag	Croatia
Length overall	41,9 m
Draft	1,2 m
No. of decks	3
Sun deck	Yes
Beam	7,6 m
Gross Tonnage	345
Summer DWT	111 t
Max speed	28 kn
Pax. Capacity	350
Propulsion	2.300 kW
Fuel use	Diesel
Consumption	491 l/h
Passenger salons	2

According to the sailing schedule for passenger ship line No. 409 (data for 2023), the daily utilization of the ship in navigation as well as in the port according to a specific part of the season is presented in the following tables.

Table 13 Number of voyages

Season	Daily	Weekly	Yearly
Off-season	Mon/Fri – 18 Sat - 10 Sun - 12	112	3.898
Low season	Mon/Fri – 20 Sat - 12 Sun - 14	126	988
High season	Mon/Fri – 22 Sat - 14 Sun - 16	140	1.916
		TOTAL	**6.802**

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Table 14 Daily ship utilization

	Port	Navigation		Berthing/Unberthing
		Time [t]	**Distance [NM]**	
	Off-season (01.01.- 01.06. / 02.10.- 31.12)			
Monday – Friday	16 h 30 min	7h 30 min	59,4	0,6 h
Saturday	19 h 50 min	4h 10 min	33,0	0,33 h
Sunday (Holiday)	19 h	5 h	39,6	0,4 h
	Low season (02.06.- 29.06. / 04.09 – 01.10.)			
Monday – Friday	15 h 40 min	8 h 20 min	66,0	0,67 h
Saturday	19 h	5 h	39,6	0,33 h
Sunday (Holiday)	18 h 10 min	5 h 50 min	46,2	0,47 h
	High season (30.06. – 03.09.)			
Monday – Friday	14 h 50 min	9 h 10 min	72,6	0,8 h
Saturday	18 h 10 min	5 h 50 min	46,2	0,47 h
Sunday (Holiday)	17 h 20 min	6 h 40 min	52,8	0,53 h

The maximum daily distance that a ship should navigate is 72,6 miles from Monday to Friday in high season.

Passenger traffic on line 409 during the observed period from 2018 to 2023 has been declining. The main reason for this is Covid-19. Compared to the year 2018, the number of passengers in 2023 has decreased by approximately 27%.

Table 15 Number of passengers

	Yearly	Daily (average)	Weekly (average)
2018	603.086	1.652	11.598
2019	578.029	1.584	11.116
2020	308.631	845	5.935
2021	428.862	1.175	8.247
2022	473.248	1.297	9.101
2023	442.120	1.211	8.502

Port infrastructure and safety standards - The passenger port of Zadar, located on the peninsula Zadar has a total of 10 berths along the 1.000-metre-long operational piers for passenger ships operating in domestic routes on regular and extraordinary routes, passenger ships on international routes, yachts, boats, fishing boats and excursion boats. Depth in the observed area in the port is 4,6 m. The Port is compliant with high safety standards.

Port of Preko is primarily intended for ro-ro passenger and passenger traffic. The total area of the port of Preko is 8,603 m^2. The port consists of two operating sections: one operating pier is 100 metres long, while the other is 40 meters long. The depth in the observed area in the port is 4,2 m. The Port is compliant with security and safety standards.

In the ports of Zadar and Preko, there are no significant navigational hazards that would endanger the safety of navigation.

Weather conditions: The most frequent wind in the observed area comes from the southern sector (jugo). Winds from this direction can reach speeds of up to 23 meters per second, with gusts of over 25 meters per second. Due to the good protection in the observed area, the influence of waves does not usually jeopardize the safety of navigation, except during strong and stormy southern winds when the line should be stopped. In the Zadar Channel, the sea currents do not usually exceed 0.5 knots.

5.2 Passenger line Mali Lošinj with the islands of Srakane Vele, Unije, and Susak

Passenger line numbered as 310 connects island of Mali Lošinj with the islands of Srakane Vele, Unije, and Susak.

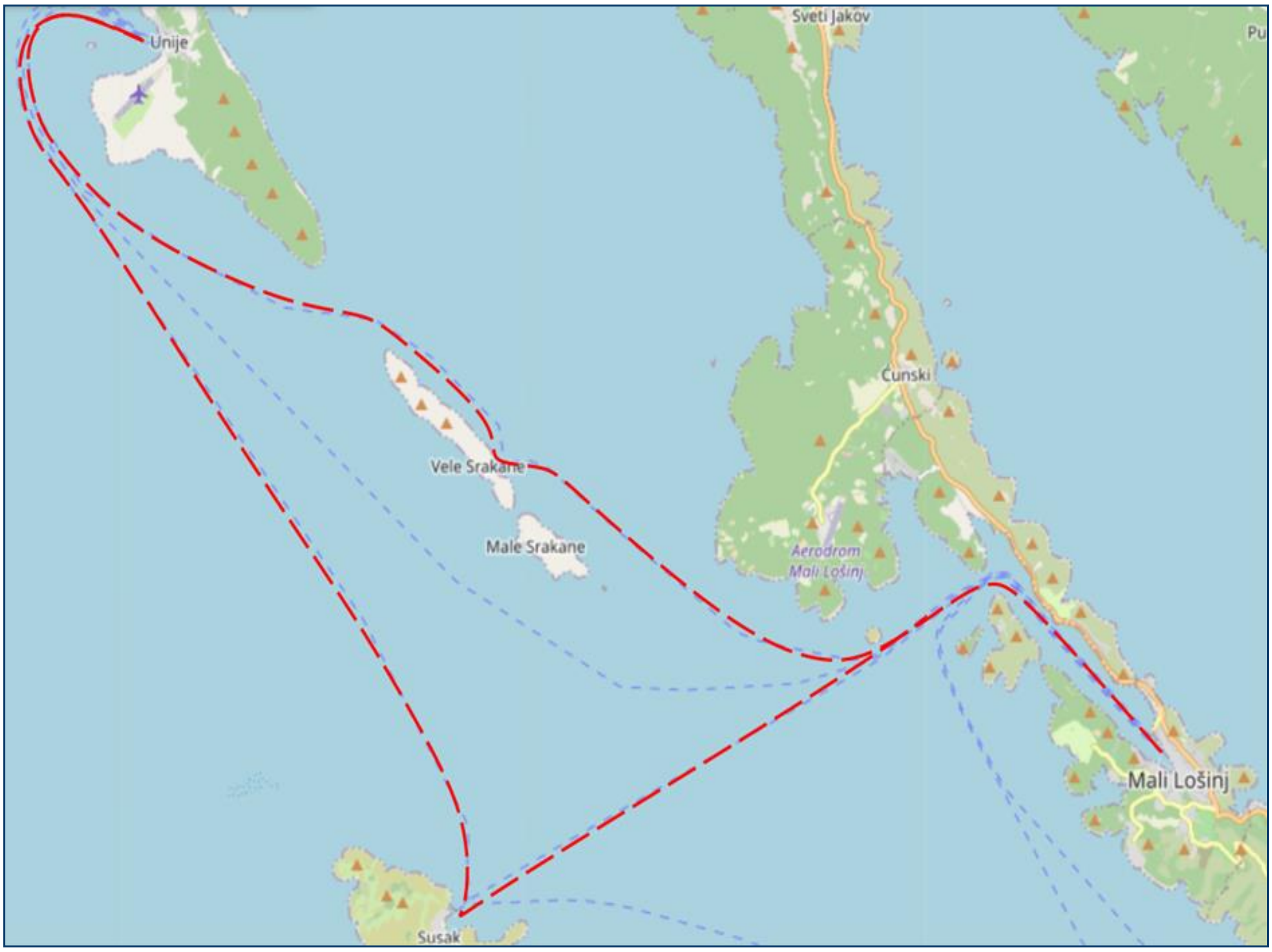

Figure 10 Passenger line 310 - Navigation route

The distance between ports is 31,4 M and the sailing time is 3 hours and 16 minutes. The values of speed, distance between ports and time of voyage are as follows:

Table 16 Characteristics of the shipping line (existing ship)

Ship status	Speed [kn]	Distance [M]	Time [min]
Unberthing	-	-	4
Manoeuvring speed	6	5,2	54
Sailing (maximum speed)	13	26,2	119
Berthing	-	-	4
Waiting time	-	-	15
TOTAL		**31,4**	**196**

Currently, on passenger line 310 Mali Lošinj – Srakane Vele – Unije – Susak – Mali Lošinj, the passenger ship "Unije" operates with the following characteristics.

Table 17 Passenger ship "Unije"

Ship type	Passenger ship
IMO No.	9289879
MMSI	238639740
Callsign	9A8467
Flag	Croatia
Length overall	46,96 m
Draft	3 m
No. of decks	3
Sun deck	Yes
Beam	7 m
Gross Tonnage	524
Summer DWT	82 t
Max speed	12,5 kn
Pax. Capacity	208
Propulsion	1.268 kW
Fuel use	Diesel
Passenger salons	2

According to the sailing schedule for passenger ship line No. 310, the daily utilization of the ship in navigation as well as in the port is presented in the following tables.

Table 18 Number of voyages

Day in week	Daily	Weekly	Yearly
Monday - Saturday	2	12	626
Sunday	1	1	52
		TOTAL	**678**

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Table 19 Daily ship utilization

	Port	**Navigation**		**Berthing/Unberthing**
		Time [t]	**Distance [M]**	
	01.01.- 31.12			
Monday – Saturday	17,9 h	5,83 h	62,8	0,27 h
Sunday	20,95 h	2,92 h	31,4	0,13 h

The maximum daily distance that the ship should navigate is 62,8 miles from Monday to Saturday equally throughout the year.

According to the data of Agency for Coastal Line Marine Transport, passenger traffic on line 310 during the observed period from 2018 to 2023 has been declining. The largest decrease in passenger traffic was recorded in 2020, with approximately 28% less compared to the previous year 2019, which is a result of the Covid-19 pandemic.

Table 20 Number of passengers

	Year	Daily (average)	Weekly (average)
2018	29.377	81	565
2019	29.066	80	559
2020	21.045	58	405
2021	26.030	71	501
2022	27.284	75	525
2023	27.136	74	522

Port infrastructure and safety standards - Port of Mali Lošinj is located on the southern side of Mali Lošinj bay. There is a dedicated passenger pier with a length of 265 meters. Depths in the observed area range from 6 to 12 meters. Port is compliant with security and safety standards.

Port of Vele Srakane is located southeast of the island of Unije. On the northeast coast, there is a pier 30 meters in length with a light (Fl(2)W 5s 6m 4M). The depth in the port is 5 m. The Port is compliant with safety standards.

The port of Unije is located on the western coast of the island of the same name. Ships mooring takes place on the inner side of the pier, which is approximately 72 meters long. There is a red light located at the head of the pier. Depth in the observed area in the port is 4,4 m. The Port is compliant with safety standards.

The port of Susak is located on the northeast coast of the island of Susak. Ships are moored at a pier 40 meters in length. There is a light at the head of the pier Fl(1)G 3s 7m 3M. The depth in the observed area in the port is 5 m. The Port is compliant with safety standards.

Weather conditions - Port of Mali Lošinj is well protected from all winds and waves due to its geographical location. The predominant currents have speeds of up to 0.3 knots. The average tidal amplitudes range from 0.3 to 0.5 meters. Strong bora winds can cause reduced visibility during navigation through the Unije Channel. In the channel, when a stormy jugo wind blows, there may be an increase in current speed up to 1.5 knots. In the port of Unije, winds from the III and IV quadrants cause choppy seas in the port and may pose a threat to navigation safety. In the port of Susak, during strong bora storms, large waves can occur, also posing a threat to navigation safety and cancelling the passenger line.

All ports on the presented lines are located on islands so hydrogen should be transported to islands with ferries. It should be mentioned that the transport of hydrogen on trucks on the ferry will include special transport requirements and regulations (e.g. use of ferry without transportation of passengers).

5.3 Passenger line Šibenik to islands

Passenger line numbered 505 connects the town of Šibenik with Vodice, namely islands Zlarin and Prvić (Prvić Šepurine and Prvić Luka) and small town Vodice.

Figure 11 Passenger line 505 – Navigation route

The total distance between ports is 9,5 miles and the sailing time is 1 hour and 26 minutes. The values of speed, distance between orts and time of voyage are as follows:

Table 21 Characteristics of the shipping line (existing ship)

Ship status	Speed [kn]	Distance [M]	Time [min]
Unberthing	-	-	4
Manoeuvring speed	6	2,3	23

Sailing (maximum speed)	11	7,2	40
Berthing	-	-	4
Waiting time	-	-	15
TOTAL		**9,5**	**86**

Currently, on passenger line 505 Vodice - Prvić Šepurine - Prvić Luka - Zlarin – Šibenik operates a passenger ship "Lara" with the following characteristics:

Table 22 Passenger ship "Lara"

Ship type	**Passenger ship**
IMO No.	8846369
MMSI	238114040
Callsign	9A4146
Flag	Croatia
Length overall	37,6 m
Draft	1,71 m
No. of decks	2
Sun deck	Yes
Beam	6,36 m
Gross Tonnage	229
Summer DWT	
Max speed	12 kn
Pax. Capacity	250
Propulsion	530 kW
Fuel use	Diesel
Consumption	73,8 l/h
Passenger salons	2

According to the sailing schedule for passenger ship line No. 505, the daily utilization of the ship in navigation as well as in the port according to a specific part of the season is presented in the following tables.

Table 23 Number of voyages

Season	Daily	Weekly	Yearly
Off-season	Mon/Sat – 10 Sun - 6	66	2.640
High season	Mon/Sat – 10 Sun - 8	68	680
		TOTAL	**3.320**

Table 24 Daily ship utilization

	Port	**Navigation**		**Berthing/Unberthing**
		Time [t]	**Distance [M]**	
	Off-season (01.01.- 21.06. / 02.09.- 31.12)			
Monday – Saturday	12,17 h	10,5 h	95	1,33 h
Sunday (Holiday)	16,9 h	6,3	57	0,8 h
	High season (22.06 – 01.09.)			
Monday – Saturday	12,17 h	10,5 h	95	1,33 h
Sunday (Holiday)	12,43 h	10,5 h	76	1,07 h

The maximum daily distance that a ship should navigate is 95 miles from Monday to Friday throughout the year.

Passenger traffic on line 505 during the observed period from 2018 to 2023 increased compared to the 2018, period before the Covid-19 pandemic. Given the growth trend, an increase in the number of passengers is expected in the coming years.

Table 25 Number of passengers (Source: Coastal Liner Passenger Services Agency)

	Daily average	Weekly average	Yearly
2018	583	4.093	212.855
2019	592	4.156	216.116
2020	398	2.794	145.312
2021	544	3.822	198.755
2022	627	4.402	228,903
2023	646	4.533	235.735

Port infrastructure and safety standards **-** Port of Vodice is located in the northern part of the Šibenik Channel. Passenger ships on this route most often dock on the outer side of the 110-meter-long pier. Depth in the observed area in the port is 3,5 m. Port is compliant with security and safety standards.

Port of Prvić Šepurine is located on the western coast of the island of Prvić. The passenger ship on this route docks on the inner side of the 70-meter-long pier. Depth in the observed area in the port is 3,9 m. Port is compliant with safety standards.

Port of Prvić Luka is located on the island of Prvić. The passenger ship on this route docks at the head of the pier. Depth in the observed area in the port is 2,8 m. Port is compliant with safety standards.

Port of Zlarin is located on the northwest coast of the island. The passenger ship on this route docks at the second pier (from the north), which is 135 meters long. Depth in the observed area in the port is 3,5 m. Port is compliant with safety standards.

The entrance to the port of Šibenik is through the St. Ante Channel. The passenger ships most often docks at the Obala Hrvatske mornarice, which is 444 meters long. Depth in the observed area in the port is 10 m. Port is compliant with high security and safety standards.

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Weather conditions - In the area of the port of Vodice, the bora wind can blow with hurricane force, posing a threat to navigation safety. Additionally, southerly and south-westerly winds, when blowing strongly or during storms, can cause rough seas. The area of the ports of Prvić Šepurine and Prvić Luka is well protected from the influence of strong winds and waves except from the southern winds. The port of Zlarin is well protected from the south, and partially from the bora wind, thus not significantly affecting navigation safety. Rough seas may result from the tramontane wind. In the port of Šibenik, the bora and southern winds blow with storm force. During strong south winds, high waves are formed. Marine currents in the NW area from the entrance to the St. Ante channel predominantly exhibit outward flow speeds ranging from 0.5 to 3 knots.

5.4 Passenger line Dubrovnik to islands Šipan, Lopud and Koločep

Passenger line numbered as 807 connects ports of Dubrovnik with islands Šipan (Šuđurad), Lopud and Koločep with the town of Dubrovnik.

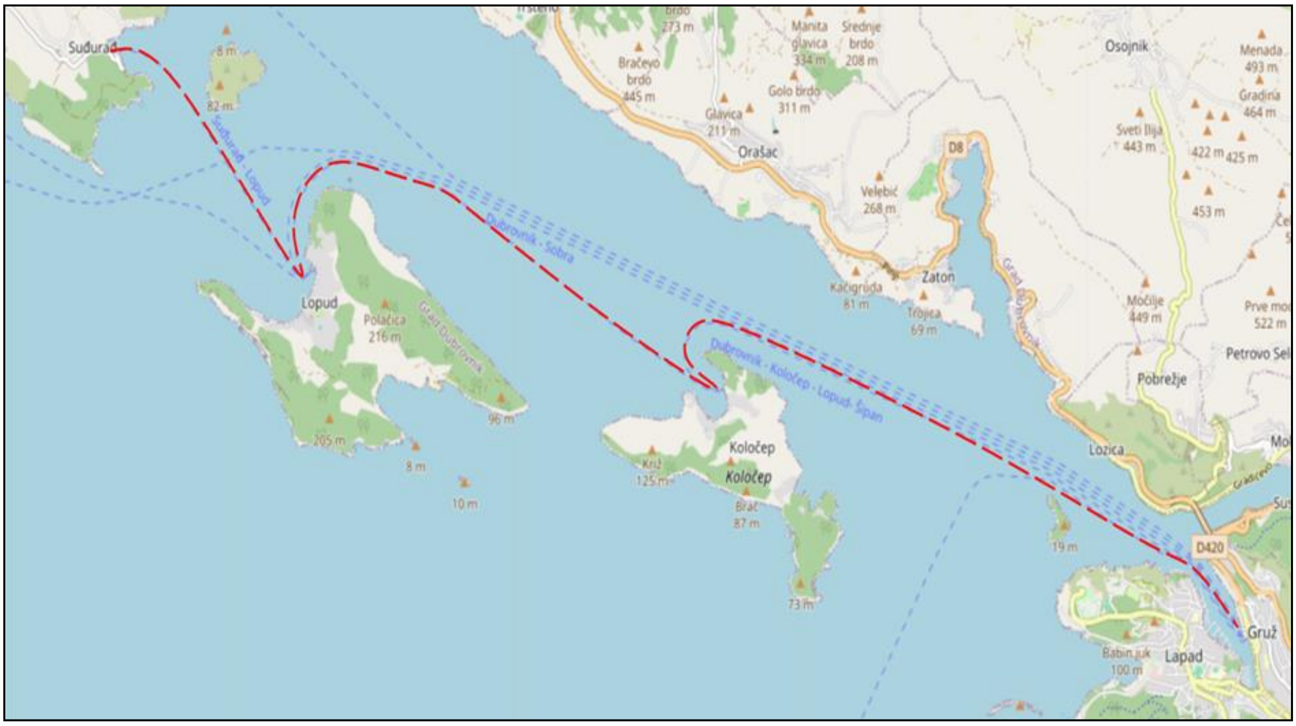

Figure 12 Passenger line 807 – Navigation route

The distance between ports is 9,9 M and the sailing time is 1 hour and 22 minutes. The values of speed, distance between orts and time of voyage are as follows:

Table 26 Characteristics of the shipping line (existing ship)

Ship status	Speed [kn]	Distance [M]	Time [min]
Unberthing	-	-	3
Manoeuvring speed	6	2,6	26
Sailing (maximum speed)	11	7,3	40
Berthing	-	-	3
Waiting time	-	-	10
TOTAL		**9,9**	**82**

Currently, on passenger line 807 Suđurađ – Lopud - Koločep - Dubrovnik, the passenger ship “Postira” operates with the following characteristics.

Table 27 Passenger ship "Postira"

Ship type	Passenger ship
IMO No.	6283202
MMSI	238114140
Callsign	9A2182
Flag	Croatia
Length overall	44,6 m
Draft	2,9 m
No. of decks	2
Sun deck	Yes
Beam	8,1 m
Gross Tonnage	361
Summer DWT	30 t
Max speed	14 kn
Pax. Capacity	380
Propulsion	882 kW
Fuel use	Diesel
Consumption	174,3 l/h
Passenger salons	1
IMO No.	6283202
MMSI	238114140

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According to the sailing schedule for passenger ship line No. 807, the daily utilization of the ship in navigation as well as in the port is presented in the following tables.

Table 28 Number of voyages

Season	Daily	Weekly	Yearly
Off-season	Mon/Sat - 8 Sun - 4	52	1.768
Low season	Mon/Sat -8 Sun - 4	52	416
High season	Mon/Sat - 8 Sun - 8	56	504
		TOTAL	**2.688**

Table 29 Daily ship utilization

	Port	Navigation		Berthing/Unberthing
		Time [t]	**Distance [M]**	
	Off-season (01.01.- 30.05. / 30.09.- 31.12)			
Monday – Friday	15,87 h	7,33 h	79,2	0,8 h
Sunday (Holiday)	19,93 h	3,67 h	39,6	0,4 h
	Low season (31.05.- 27.06. / 02.09 – 29.09.)			
Monday – Friday	15,87 h	7,33 h	79,2	0,8 h
Sunday (Holiday)	19,93 h	3,67 h	39,6	0,4h
	High season (28.06. – 01.09.)			
Monday – Friday	15,87 h	7,33 h	79,2	0,8 h
Sunday (Holiday)	15,87 h	7,33 h	79,2	0,8 h

The maximum daily distance that the ship should navigate is 79,2 miles from Monday to Friday and it is required throughout the whole year.

According to the date of Agency for Coastal Line Marine Transport, passenger traffic on line 807 during the observed period from 2018 to 2023 has been declining. The main reason for this is Covid-19 pandemic.

Table 30 Number of passengers

	Yearly	Daily (average)	Weekly (average)
2018	240.181	658	4.619
2019	236.753	649	4.553
2020	112.915	309	2.171
2021	155.792	427	2.996
2022	214.045	586	4.116
2023	209.373	574	4.026

Port infrastructure and safety standards - Port of Suđurađ is located on the island of Šipan. In the harbour, the passenger ship berth on the eastern side of the pier, which is 19 meters long. Depth in the observed area in the port is 3,8 m. Port is compliant with safety standards.

Port of Lopud is located on the island of Lopud. A 38-meter-long operational pier is used for berthing public ferry traffic. Depth in the observed area in the port is 3,4 m. Port is compliant with safety standards.

Port of Koločep accommodates the ship on the southern side of the 65-meter-long pier. Depth in the observed area in the port is 4,4 m. Port is compliant with safety standards.

In the port of Dubrovnik, ships on the line 807 dock at the head of the Petka pier, which is 30 meters long. Depth in the observed area in the port is 5,7 m. Port is compliant with safety standards.

Weather conditions - In the observed area, the most common winds (southern direction) in the winter months can generate waves exceeding 3 meters in height and pose a threat to navigation safety. The largest waves occur when winds blow from the south when the passenger line should be stopped.

6 FINDINGS

ZEAS project feasibility study elaborates and evaluates options and possibilities for the development of hydrogen-powered ship. The study is based on the ship's performance and design requirements given by project partner Jadrolinija who intends to operate the ship. The main ship characteristics are: ship length is 38 m with a passenger capacity of 250 and an operational range of a minimum 100 NM. The ship is intended to sail on one of the domestic (Croatian) passenger lines which was chosen as the appropriate line following the project proposal and the ship's characteristics. The lines connect different ports on islands in Croatia, namely Zadar – Preko, Mali Lošinj – Vele Srakane – Unije – Susak, Vodice – Prvić Šepurine – Prvić Luka – Zlarin – Šibenik and Suđurađ (Šipan) – Lopud – Koločep – Dubrovnik.

In general, typical hydrogen-powered ships that is operated at the moment are relatively small passenger ships with lengths up to 50 m which match the size of the ZEAS project ship.

A comprehensive legal framework explicitly designed for hydrogen-powered ships is currently lacking. Different classification societies have already implemented classification rules. Regarding the ZEAS project and its implementation, one of the classification rules that have already been developed for hydrogen-powered ships should be implemented, while the Croatian Register of Shipping, as classification society responsible for the classification of ships in national waters, need to develop rules for hydrogen-powered ships. Furthermore, the Interim guidelines for the safety of ships using Hydrogen as fuel and full requirements for hydrogen fuel cell-powered ships which is currently under development by the IMO is intended to be in force by 2025.

Regarding the design of hydrogen-powered passenger ship of similar sizes, the preferred locations for passenger areas and communication routes are forward or aft deck, i.e. areas that typically offer ample space for passenger queuing and directing to the gangway.

Hydrogen engines for marine propulsion are still in the development stage while hydrogen fuel cells are already operational. Detailed elaboration of the advantages and disadvantages of the H2 engines and types of fuel cells is presented in the study. For ZEAS project ship, the most viable option is fuel cell PEMFC (Polymer Electrolyte Membrane Fuel Cells) type due to their maturity, compactness, fast response, acceptable efficiency and relatively lower cost compared to other systems. In addition, fuel cell presents more economical solutions, offering potential savings from 20€ - 141 € per hour during sailing at rated power depending on the actual hydrogen price. However, the potential economic benefits of using fuel cells rely greatly on the present hydrogen price on the market.

During the ship’s design phase, it is highly recommended to simulate the overall ship’s power consumption (propulsion and all auxiliary systems) during navigation, manoeuvring and ship’s stay in order to calculate the optimal battery capacity for the referent ship.

For the ship foreseen by ZEAS project, the recommended storage of hydrogen is in gaseous form (compressed state) and recommended size of hydrogen tanks will be designed for an estimated total capacity of 350 kg. The suitable range of pressure for compressed hydrogen storage is between 250 and 750 bar at ambient temperatures (10 - 30°C). Also, gaseous hydrogen requires several tanks to optimize space requirements and to offer the possibility of replacing single tanks presenting with small cracks or any defects. The total storage for the required 350 kg capacity at 300 bar and 20°C would require a total volume of approximately 17,5 m^3 as the hydrogen density for the given thermodynamic parameters is approximately 20 kg/m^3. The volume of the storage system should be defined after defining the filling dynamics considering the temperature reached by the hydrogen during the refilling process. Adequate position of the hydrogen tanks on board a ship (“International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels”) is on the top deck and astern close to the FCS.

The feasibility study present preliminary findings related to development and implementation of hydrogen powered passenger ship with presented design requirements. Further examination will be carried out during implementation of ship concept design.

REFERENCES

[1]. ABS, Requirements for Hydrogen Fueled Ships, 2023

[2]. ABS, Guide for fuel cell power systems for marine and offshore applications, 2019

[3]. Ariel Chiche, On Hybrid Fuel Cell and Battery Systems for Maritime Applications, Doctoral Thesis in Chemical Engineering, KTH Royal Institute of Technology, Sweden, 2022.

[4]. A review of the Feasibility of Utilising Hydrogen as a Marine Fuel in Australia, Aus Industry, Cooperative Research Centres Program 2023

[5]. Fan, H., Abdussamie, N., Harris, A., Chen, P. S.-L., Gray, E., Arzaghi, E., Bhaskar, P., Mehr, J. A., & Penesis, I., A review of the feasibility of utilising hydrogen as a marine fuel in Australia, Blue Economy Cooperative Research Centre, 2023.

[6]. GOING GLOBAL, An update on Hydrogen Valleys and their role in the new hydrogen economy, Clean Hydrogen Partnership, 2022. https://h2v.eu/

[7]. IMO, Interim guidelines for the safety of ships using fuel cell power installations, MSC.1/Circ.1647, 2022.

[8]. Joseph W. Pratt and Leonard E. Klebanoff, Feasibility of the SF-BREEZE: a Zero-Emission, Hydrogen Fuel Cell, High-Speed Passenger Ferry, Sandia National Laboratories, 2016.

[9]. Office of energy efficiency & renewable energy, US department of Energy, Washington DC: https://www.energy.gov/eere/fuelcells/types-fuel-cells

[10]. Technology Outlook 2030, DNV-GL.

[11]. Zero emission industries: https://www.zeroei.com/work/sea-change

[12]. https://h2v.eu/analysis

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