TransH2

D.2.2.3 - Two passenger ship conceptual design for regional and cross-border connection

Deliverable 2.2.3

Responsible partner: Navalprogetti Srl

Involved partners: NAVALPROGETTI

Version	Status	Date	Author
0.1	Draft	23.01.2026	NAVALPROGETTI
1	Final	29.01.2026	NAVALPROGETTI

Notes:

CONTENT INDEX

TABLES INDEX

FIGURES INDEX

1 Project Overview

The assessment of the Interreg ITA-CRO program area identifies a considerable presence of ports along the Adriatic coast and highlights the critical need to advance the sustainability of port infrastructures. This will be achieved by adopting low-carbon transportation and mobility solutions, particularly through the modernization and sustainability of maritime connections. The primary goal of the TransH2 project is to improve sustainable sea mobility by showcasing viable applications of zero-emission fuels, such as green hydrogen, in maritime transport routes. This involves the introduction of these innovations to port authorities, transport operators, and stakeholders across the region.

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

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

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

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

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

2 Activity 2.2 Overview

2.1 Objectives

The Activity 2.2 – *Joint research and development of conceptual design on innovative concepts for hydrogen fuelled passenger ships for local and cross-border maritime traffic* focuses on the collaborative research and development of conceptual designs for two passenger ships for regional and cross-border connections in the Adriatic Sea. The ships will incorporate hydrogen propulsion. The conceptual design will address critical technical, regulatory, and economic aspects, integrating innovative solutions for sustainable maritime mobility.

The project will facilitate cross-border collaboration, with partners PFRI, mareFVG, NAVPRO, START, and UNITS working together on design co-creation. Additionally, an Independent Evaluation Expert conducted a mid-term review (D.2.2.1) and a later assessment (D.3.3.1) to measure project progress, risk factors, and overall impact.

2.2 Scope of work

Building upon insights from Activity 2.1, the Activity 2.2 will explore optimal machinery configurations in terms of hydrogen storage technology and energy conversion technology. Key elements of the design process include:

- Review of the state of the art, applicable local regulations, and operational requirements.
- General arrangement plan to define ship layout and spatial organization.
- Technical specifications, including stability evaluations, power predictions, and an energy balance analysis.
- Preliminary electrical system design and bunker station arrangement for safe hydrogen refuelling.
- Hazardous area planning and emergency shut-down philosophy for safety compliance.
- Economic feasibility assessment, including CAPEX and OPEX estimations.
- 3D modelling and visual materials to support design validation.
- Stakeholder engagement and collaborative peer review, ensuring cross-border knowledge exchange.
- Targeted communication activities, such as infographics, video clips, and social media outreach, to raise awareness of hydrogen-based maritime solutions.

3 Executive Summary

This report on the TransH2 project presents an in-depth analysis of the optimal configuration for hydrogen-powered passenger ships, summarising research findings, technical assessments and peer-reviewed opinions.

As maritime transport faces increasing pressure to decarbonise, hydrogen is emerging as a promising zero-emission alternative, offering a clean and sustainable energy source for ferry operation. The paper explores key technical aspects, including the most effective machinery configurations, propulsion architectures, and energy system layouts. These have previously been analysed in the comparative analysis of various hydrogen storage and energy conversion technologies, as per Ref. [15] and [16]. The aim of these analyses was to assess their feasibility in terms of energy efficiency, operational practicality, and environmental impact.

A key component of this study was the multi-criteria assessment, which examined various configurations of hydrogen-powered ships against key performance indicators such as energy storage density, energy conversion system efficiency, storage costs, etc. Particular attention was paid to regulatory frameworks and safety considerations, ensuring that the proposed configurations are in line with international maritime safety standards.

In consideration of the results obtained from Pilot 1 activities, the present deliverable implements the conceptual design for two small passenger ships intended for utilisation in the context of regional and cross-border connections within the Adriatic Sea. The development of the ship's design is based on hydrogen propulsion, with hydrogen storage in pressurised tanks and a power generation train based on PEM fuel cells.

4 Introduction

The maritime industry is currently undergoing a transformation driven by stringent emissions regulations, technological advancements, and increasing environmental concerns. The International Maritime Organization (IMO) has set ambitious targets for greenhouse gas reduction, calling for zero- emissions from international shipping by 2050 and aiming for full decarbonization within the century. As a response, hydrogen has emerged as one of the most promising alternatives to conventional marine fuels due to its high energy density, zero-emission potential and compatibility with fuel cell technology. Unlike fossil fuels, hydrogen combustion or fuel cell conversion does not produce carbon dioxide, particulate matter, or sulfur oxides, making it an ideal candidate for sustainable maritime applications. However, the successful implementation of hydrogen-powered ships requires addressing several critical challenges, including fuel storage, energy conversion efficiency, safety considerations and infrastructure development. This report serves as a comprehensive analysis of the optimal configuration for hydrogen-powered passenger ships, with a particular focus on identifying the most efficient propulsion architectures and energy system layouts. The findings presented herein build upon previous research and technical assessments conducted within the TransH2 project, incorporating peer-reviewed studies and insights from real-world applications of hydrogen propulsion in maritime environments.

The selection of energy conversion systems, hydrogen storage solutions, and hybrid propulsion architectures has been the focus of particular attention. The objective of this focus was to optimise ship performance while ensuring operational reliability and cost efficiency, see Ref. [18]. The report also examined regulatory and safety considerations, given that hydrogen, while offering significant environmental benefits, presents unique handling and operational risks that must be mitigated through robust design and engineering solutions.

As part of the TransH2 project's broader objectives, this report does not merely provide a theoretical overview of hydrogen-based ship propulsion but also serves as a foundation for real-world implementation. The conclusions drawn from this study will directly contribute to the next phases of the project, particularly the development of prototype ships and the establishment of fuelling infrastructure at key maritime hubs in the Adriatic region. By synthesizing data from multiple sources, including previous Interreg maritime transport studies, international best practices, and experimental pilot projects, this document aims to provide a clear roadmap for ship designers, policymakers, and industry stakeholders who are working toward a greener maritime future.

Ultimately, this report will serve as a strategic guide for making informed decisions on optimal ship configurations, helping to pave the way for an efficient, safe, and economically viable hydrogen-powered maritime transport network. The following sections will delve into the methodologies used in this study, the state of the art in hydrogen propulsion, the technical and environmental considerations shaping optimal configurations, and the recommendations for future implementation.

5 References

5.1 Rules references

[1]	IGF Code, 2016
[2]	CCC 6/WP.3, Annex 2 (COMMITTEE ON CARRIAGE OF CARGOES AMN CONTAINERS) – Amend. IGF Code
[3]	SOLAS, 2014
[4]	ISO 15916, 2015
[5]	ASME B31.3, 2016
[6]	ASME B31.12, 2014
[7]	IEC 60079, 2016
[8]	IEC 62282, 2019
[9]	ANSI/AIAA G-095A, 2017
[10]	IGC Doc 121/14 - HYDROGEN PIPELINE SYSTEMS
[11]	EN ISO 11114 Gas cylinders - Compatibility of cylinder and valve materials with gas contents
[12]	IMO Intact Stability Code (IMO 2008 IS Code)

Table 5-1: Rules references

5.2 Project references

[13]	D.2.1.1	Joint report on analysis of maritime passenger routes for case-studies
[14]	D.2.1.2	Follow-up report from online workshop for use-case development
[15]	D.2.1.3	In-depth analysis and transport models for 3 use-cases
[16]	D.2.1.4	Option analysis for introduction of hydrogen fuelled solutions in 3 use-cases
[17]	D.2.2.1	Mid-term external review
[18]	D.2.2.2	Report on optimal configuration for 2 different hydrogen fuelled passenger vessels
[19]	D.2.3.1	Technical report on analysis of hydrogen fuelling stations in existing port infrastructures
[20]	D.2.3.2	Cross-border port hydrogen refuelling feasibility study

Table 5-2: Project references

6 Abbreviations and Acronyms

The following acronyms and abbreviations are introduced in the document:

Acronym/Abbreviation	Explanation/Definition
AC	Alternating current
BESS	Battery Energy Storage System
BL	Bale line
BOP	Balance of Plant
BP	Brake Power
CL	Centre Line
CWHR	Cooling water heat recovery
DC	Direct current
DN	Nominal diameter
Ex. Zone	Explosion Zone
FCS	Fuel cell system
FEM	Finite Element Method
FSM	Free surface moment
Fr. (fr.)	Frame, position from aft perpendicular
FW	Fresh water
GA Plan	General Arrangement Plan
GH2	Gaseous hydrogen
H2	Hydrogen
HAZ	Hazardous Area Zone
HT	High temperature
HV	High Voltage
HVAC	Heat, Ventilation, Air Condition
ID	Inner diameter
IEC	International Electrotechnical Commission
IGC	International Code of the Construction and Equipment of Ships Carrying
IGF	International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels

IMO	International Maritime Organization
kn	Knot (1852 m in 1 hour)
LCG	Longitudinal position centre of gravity
LT	Low temperature
LV	Low Voltage
MCR	Maximum continuous rating
N2	Nitrogen
NA	Not applicable
nm	Nautical mile (1852 m)
PBU	Pressure buildup unit
PEMFC	Proton exchange membrane fuel cell
PMS	Power management system
PN	Nominal pressure
PP	Perpendicular
PRV	Pressure relief valve
PS	Portside
SB	Starboard
SC	Shore connection
SOLAS	International Convention for the Safety of Life at Sea
SW	Sea water
TBC	To be confirmed
TBD	To be defined
TCG	Transverse position centre of gravity
VCG	Vertical position centre of gravity
ZEM	Zero emission mode

Table 6-1: Abbreviations and Acronyms

7 State of the Art and applicable rules and regulations

The international regulatory framework for hydrogen use in marine applications is still in development. The assessment of hydrogen storage, handling, and fuel cell installations on ships relies primarily on a combination of risk-based approaches, existing maritime regulations, and standards from industrial sectors where hydrogen is already widely used, such as petrochemical and energy industries. This ensures that new designs achieve a safety level equivalent to conventional systems.

7.1 Overview of Maritime Regulations

IMO and IGF Code

The International Maritime Organization (IMO) governs international ship safety through various sub-committees, including the Marine Safety Committee (MSC) and the Sub-Committee on Carriage of Cargo and Containers (CCC). The IGF Code, effective since January 2017, regulates the use of low-flashpoint fuels on ships over 500 GT, including liquefied natural gas (LNG). For fuels other than LNG, such as hydrogen, the IGF Code relies on an "Alternative Design" approach based on risk assessments. Fuel cell installations are also addressed in IMO Draft Interim Guidelines (CCC 6/WP.3, Annex 2), but detailed prescriptive rules for hydrogen use as a marine fuel are not yet established.

SOLAS

The International Convention for the Safety of Life at Sea (SOLAS) sets minimum safety requirements for ship construction, equipment, and operation. While SOLAS does not include hydrogen-specific rules, it allows deviations from standard regulations via risk-based alternative design approaches. Key chapters relevant to hydrogen projects include II-1 (ship structure and machinery), II-2 (fire protection), and carriage of dangerous goods regulations. Risk assessments must consider hydrogen storage location, potential leakage, and high-consequence scenarios.

IGF Code

The International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code) establishes mandatory safety requirements for ships using low-flashpoint fuels for propulsion and auxiliary power. The Code primarily addresses LNG systems, while hydrogen is not yet explicitly included as a prescriptive fuel. However, the IGF Code adopts a goal-based and risk-based approach, allowing alternative fuel concepts such as hydrogen to be assessed through equivalency and alternative design provisions. Key safety aspects include fuel containment systems, ventilation, gas detection, hazardous area classification, and emergency shutdown arrangements. Ongoing IMO developments and interim guidelines are expected to further clarify technical requirements for hydrogen as a marine fuel.

7.2 International Standards

ISO

ISO/TR 15916:2015 provides general guidelines for hydrogen safety, including storage, handling, and system components. It identifies primary components (e.g., fuel cell stacks) and auxiliary components (e.g., hydrogen storage, flow controls, pressure relief systems, detection apparatus). The standard emphasizes welded joints for leak-sensitive applications, monitoring of flow and pressure, and safety measures for hydrogen release. Hydrogen's environmental impact is minimal, as escaped gas either oxidizes or dissipates into the atmosphere.

ASME

The American Society of Mechanical Engineers (ASME) publishes piping standards relevant to hydrogen systems:

- **B31.3 – Process Piping:** Covers chemical, cryogenic, and industrial piping.
- **B31.12 – Hydrogen Piping and Pipelines:** Provides engineering requirements for safe hydrogen transport and handling, including pressure, flow, material selection, and vibration control. While not marine-specific, ASME standards offer essential guidance for safe piping design and operational integrity.
-

IEC

The International Electrotechnical Commission addresses electrical safety and compatibility, particularly for areas exposed to hydrogen:

- **IEC 60079:** Explosive atmospheres, including hazardous area zoning, ventilation, and ignition prevention.
- **IEC 60092-502:** Electrical installations on ships carrying flammable liquids or gases.
- **IEC 62282:** Fuel cell technologies, including performance and safety considerations. These standards help inform electrical integration and safety management for hydrogen fuel systems on board.

7.3 Risk-Based Design Approach

Given the lack of prescriptive rules for hydrogen as a marine fuel, risk assessments are central to demonstrating equivalent safety levels. This includes:

- Evaluating normal operations and failure/emergency scenarios.
- Assessing hydrogen storage placement, potential leak points, and environmental effects.
- Applying alternative design approaches consistent with Class Society approval.

Existing standards from terrestrial hydrogen use, petrochemical rules, and LNG regulations provide valuable references for materials, piping, insulation, pressure relief systems, and operational procedures. Continuous updates are expected as IMO, flag states, and classification societies release new guidelines.

8 Passenger ship concept design for regional routes

The shipping industry is under increasing pressure to act upon the Conference of the Parties 21 Paris Agreement, the new carbon dioxide (CO2) reduction targets from the International Maritime Organization (IMO), and to reduce greenhouse gas (GHG) emissions in general. Shipping must achieve large emissions reductions over the next decades. Local and regional air pollution will in future face tougher regulations worldwide. Following reductions in air pollutants from other sources, particularly from industry and land transport, the marine sector may be expected to account for a larger percentage of emissions, and to face increased societal pressure to reduce them. The next big deadline for the industry is 2050. The IMO's commitment to halve emissions from shipping by 2050 sets an ambitious target for the maritime world. Alternative and zero carbon fuels offer a pathway to achieve this goal, but there are still challenges with all alternative energy carriers / fuels. Liquefied natural gas (LNG) and liquefied petroleum gas (LPG) are fossil fuels. Ammonia is currently produced from fossil natural gas and is toxic. Biofuels face sustainability challenges, high costs, and limited availability. All-electric solutions are limited to ferries and short distances. Within short-sea shipping, and even for transportation on urban waterways.

Many stakeholders consider hydrogen as a viable solution for coastal and short-sea shipping. It can be a more flexible energy carrier, can facilitate onboard storage of more energy than batteries, and it is also more suitable for transport to bunkering sites. Hydrogen fuel cells might be the only zero-emission alternative given the lack of sustainable biogas. Whether hydrogen is a truly zero-emission option depends on the value chain and whether it is produced from renewable energy sources.

The aim of the proposed marine transport solution to achieve the targets of zero emission with a passenger and car ferry for regional transport with the installation on board of a PEM FC (Proton Exchange Membrane Fuel Cell) electric energy production system to feed the ship's electric grid, in combination with the energy provided by BESS (Batteries Energy Storage System).

The solution consists of using gaseous hydrogen, stored on board and employed in PEM FC stacks to produce electric energy. The gaseous hydrogen is transferred on board through a dedicated bunker station. The gaseous hydrogen can be transferred onboard from an onshore bunkering facility through loading arms.

As outlined in the project documentation previously issued (D.2.1.4), two different regional routes are currently under consideration:

- The Croatian Regional Route, connecting Split and Supetar.
- The Italian Regional Route, connecting Tronchetto and Lido.

The above two routes are distinguished by two key elements:

- the installed propulsive power
- the required range

These elements are fundamental to differentiating the two routes and, consequently, the two concept designs.

- Croatian Regional Route (Split-Supetar)

A cruising speed of 11 knots has been selected for this route. This speed is compatible with the size of the ship and the service it is to provide. In order to keep the requisite service speed, the ship is equipped with a propulsion power of 1000 kW. The route extends for 8.6 nautical miles, with seven round trips conducted daily, with two refuelling operations per day. This results in a range of 60 nautical miles per refuelling. The storage capacity for compressed hydrogen at 350 barg requires the use of seven cylinders (Type III, composite wrapping, steel lining).

- Italian Regional Route (Tronchetto-Lido)

The cruising speed is reduced to 6 knots in order to comply with the speed restrictions imposed by the Municipality of Venice for inland navigation. Consequently, the propulsion power can be substantially reduced to 350 kW. The storage capacity for compressed hydrogen at 350 barg requires the use of only 3 cylinders (same type and size as those used in the Croatian Regional Route). This reduction in number is due to the lower installed power and the shorter range required on this route, which is 3.8 nautical miles and is travelled 20 times a day (10 round trips) ,with two refuelling operations per day. The range is 38 nm per refuelling.

Therefore, the two concept designs will differ only in terms of FC installed power, azimuth thrusters power, the Li-ion battery pack capacity and the number of H2 compressed cylinders. All other characteristics (dimensions, cars & passenger intake, etc) remain the same for the two different configuration.

8.1 General arrangement plan

General arrangement has been developed including the hydrogen propulsion system. The hydrogen storage system is composed by Type III cylinders (composite wrapping, steel lining). Hydrogen is stored in gaseous form at 350 barg. The storage is arranged underdeck in a dedicated room.

PEM fuel cells are arranged in two separated spaces for a redundant configuration. The battery system is installed in a dedicated space separated from FC room by a cofferdam.

Switchboards and power management system are located in Control Room.

The General arrangement plan is shown below.

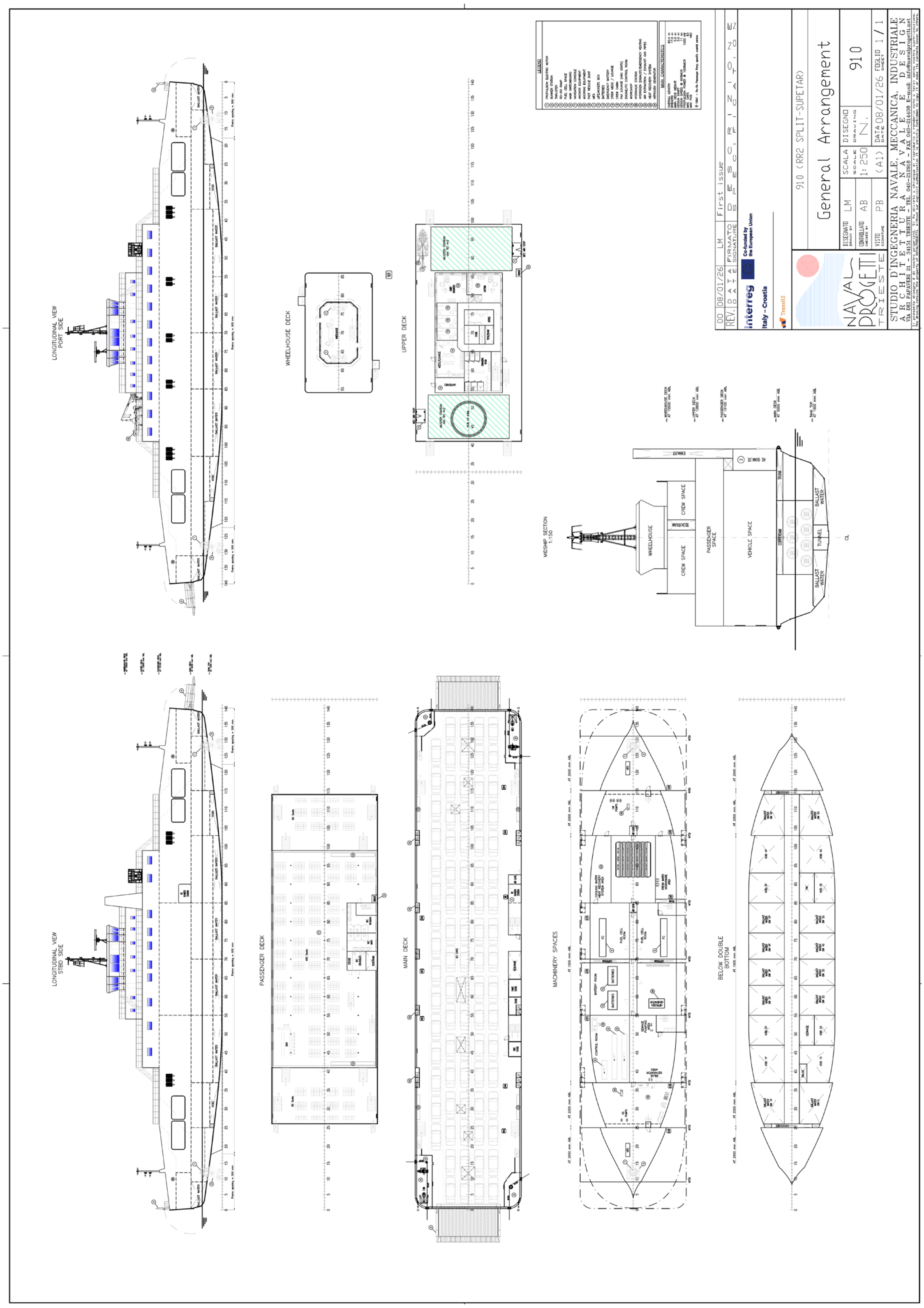


Figure 8-1: Regional Route ship General Arrangement

8.2 Outline specification

8.2.1 General

8.2.1.1 Introduction

This outline specification describes the ship main characteristics as well as the main propulsion system fuelled by gaseous hydrogen. The ship will be capable to operate with zero emission by means of PEM FC and battery storage. The gaseous hydrogen is stored in cylinders with a pressure of 350 barg.

8.2.1.2 Operating area

The ship will operate in regional coastal area for daily service. Two typical regional routes have been considered:

Route name		Split-Supetar	Tronchetto-Lido
Route length	nm	8.6	3.8
Route service speed	kn	11.0	6.0
Number of trips in one day		14	20

Table 8-1: Regional Routes main characteristics

The route paths are illustrated in the Figure 8-2: Croatian Regional Route Split – Supetar and Figure 8-3: Italian Regional Route Tronchetto – Lido.

Figure 8-2: Croatian Regional Route Split – Supetar

Figure 8-3: Italian Regional Route Tronchetto – Lido

8.2.1.3 Ship description

With reference to the General Arrangement Plan:

General

- The ferry shall have a symmetrical double ended configuration as it is suitable for boarding vehicles from both ends via two main movable ramps.

Double Bottom

- Ballast tanks should be arranged on this level.

Bottom Deck

- Main liquid tanks shall be arranged on this level.
- At the hull ends two symmetrical engine rooms with relative azimuthal thruster shall be in accordance with General Arrangement Plan.
- In the central area shall be located the Control Room with a control console (for fuel cells, battery management system, propulsors) and a main switchboards.

Below the Main Deck the following ship services shall be located:

- bilge system;
- sewage treatment system;
- fresh water system;

Main Deck

- 83 cars with dimensions and relative distances between them (600 mm) shall be arranged.
- Nr.4 lifejacket boxes with capacity for 1000 passengers shall be arranged on this level.

Passenger Deck

- 480 passengers shall be accommodated. Inside the superstructure shall be provided 160 seats.
- Inside the superstructure bathrooms with easy access for passengers with disabilities shall be arranged.
- A dedicated stair trunk for the crew shall connect the various technical rooms on the main deck with those on the lower levels.

Upper Deck

- Inside the superstructure Nr.3 single private rooms, Nr.2 private rooms with toilet, Nr.3 common toilets, Nr.1 lounge room, Nr.1 office shall be arranged.
- In the forward area Nr.1 self-propelled rescue boat with davit shall be arranged.
- A dedicated stair trunk connected to the wheelhouse shall be arranged.
- Battery locker for emergency battery.

Wheelhouse Deck

- Nr.2 control console and a dedicated movable seat between them shall be installed.

- The wheelhouse shall have a suitable false floor to accommodate all connections between the engine control room console and the wheelhouse deck consoles.
- Wheelhouse shall be completed with all equipment necessary to navigation and communication (mast signals, antennas, radar, compass etc.)

8.2.1.4 Ship main characteristics

Description	Symbol	Value	Unit
Length Overall	LOA	80.40	[m]
Length at Waterline	LWL	78.60	[m]
Max. Breadth	B	17.00	[m]
Breadth at Waterline	BWL	15.40	[m]
Depth	H	5.00	[m]
Max Draft	T	3.00	[m]
Service speed	v	11.0	[kn]
Power @100%MCR	Pprop	1000	[kW]
Cars	-	83	-
Person on board	-	480	-

Table 8-2: Ship main characteristics

8.2.2 Speed and power

The maximum power of 1000 kW (2x500) shall be suitable to ensure a speed of at least 11.0 kn at 85% of MCR.

8.2.3 Power plant

The ship shall be equipped by a zero emission propulsion and power plant. The system will be composed by hydrogen powered PEM fuel cell and a battery storage.

The hydrogen will be stored in gaseous form in compressed cylinders filled through a dedicated bunker station.

The ship energy management system will control fuel cell, batteries, propulsions system and will optimize ship energy consumption and fuel cell and battery usage.

8.2.4 Battery storage

A power pack with lithium batteries shall be provided for fuel cells peak shaving, fuel cell buffer and safe return to port.

The battery storage shall be arranged in a dedicated room as per General Arrangement.

The total battery power installed shall be 700 kWh.

The battery pack shall be of sealed type and water cooled.

Fire detection system and suitable fire extinguishing system shall be installed in battery room.

The BMS shall be connected to ship PMS for energy management.

8.2.5 Hydrogen storage

Hydrogen in gaseous form shall be stored on board to feed fuel cell systems.

A total of seven (7) gas cylinders shall be arranged in a dedicated ship storage area. For the Italian Regional Route Tronchetto-Lido the number of cylinders is reduced to three (3).

The gas cylinders shall be of Type III (composite wrapping, steel lining).

The gaseous hydrogen shall be stored at a pressure of 350 barg.

The storage system shall be provided of suitable relief valves for emergency gas release. Hydrogen venting shall lead to venting mast.

The storage area shall be provided of suitable ventilation, fire and gas alarm.

8.2.6 Fuel cell system

The ship will be provided by PEM fuel cell for propulsion and auxiliary power. The total installed capacity shall be 1200 kW. Fuel cells modules shall be arranged in two different rooms for redundancy requirements, each room with equal fuel cells total power installed.

Here below are reported the characteristics of one fuel cell module only for reference (e.g. Ballard).

Product Specifications

Performance	
Rated power	200kW
Minimum power	55kW
Peak fuel efficiency	53.5%
Operating voltage	350 – 720 V DC
Rated current [1]	2 x 300 A or 1 x 550 A
System cooling output	Max 65° C
Stack technology	
Heat management	Liquid cooled
H_2 Pressure	3.5 – 6.5 barg
Physical	
Dimensions (l x w x h) [2]	1209 mm x 741 mmx 2195 mm
Weight (estimate) [3]	1000 kg
Environmental protection	IP44
Engine room (DNV CG-0339)	+0°C – +45°C
Minimum start-up temperature	0°C
Short-term storage temperature	-40°C – +60°C
Reactants and Coolant	
Type	Gaseous hydrogen
Composition	As per SAE spec. J2719 and ISO 14687:2019 Type I, Type II – Grade D
Oxidant	Air
Composition	Particulate, Chemical and Salt filtered
Coolant [4]	Water or 50/50 glycol
Safety Compliance	
Certifications	DNV-Type Approval , Lloyds Register Approval and ABS (American Bureau of Shipping) Approval
Enclosure	Sealed secondary barrier for hydrogen
Monitoring	
Control interface	Ethernet, CAN
Emissions	
Exhaust	Zero-emission

Table 8-3: Typical fuel cell module characteristics

The fuel cell modules shall be liquid cooled. Suitable cooling, venting, drain and inerting systems shall be provided to fuel cells modules. Adequate redundancy of auxiliary systems shall be provided in case of system one single failure.

Hydrogen feeding pipes from hydrogen storage bottles to FC shall be stainless steel and double walled type.

The fuel cell system shall be controlled by ship PMS.

8.2.7 Bunker station

Ship shall be provided of one bunker station at starboard, as represented in the General arrangement.

The bunker station will be equipped with one or two connections for gaseous hydrogen filling, in order to meet the total flow rate requirements, and one cable connection for the ESD system.

Bunker gas manifold shall be isolated by two valves as required by IGF code. Pressure relief valve shall be provided to bunker gas manifold leading to vent mast.

The gas pipe coupling shall be of quick release type.

The bunker station shall have gas and fire alarm.

A fire extinguishing system shall be provided in bunker station area.

8.2.8 Auxiliary systems

8.2.8.1 Inerting system

Inerting is done to minimise the level of oxygen in a given space and prevent oxygen and/or moisture from coming into contact with reactive or adsorptive products.

The main aim of the inerting are to:

- Prevent explosive atmospheres from forming;
- Ensure safe startup and shutdown of plants and apparatus;
- Avoid explosion risks during storage and transport of combustible substances;
- Protect products against atmospheric oxygen when oxidation reactions would impair quality;
- Protect against atmospheric moisture, either to maintain product quality or to ensure optimal downstream processing;

- Prevent health and safety hazards during maintenance of plants, apparatus and pipelines;

Purging process introduces an inert gas in the pipeline in order to displace a gas from it.

The inert gas systems shall include the nitrogen inert system for inertization of gaseous hydrogen system;

Nitrogen system shall be provided for the purging/inertization of the piping system;

Purging of piping system shall be performed with displacement method. The inert gas system shall have the capability to purge hydrogen from gaseous piping system lowering the hydrogen concentration below 4%.

Nitrogen shall be produced by a nitrogen generator and stored in compressed cylinders of 50 l each at abt. 300 bar with purity of 99.99% in a dedicated storage room.

Each hydrogen pipe section between two segregation valves shall be provided with connection to inerting system.

8.2.8.2 Venting system

Venting system shall be designed in order to safely vent hydrogen from hydrogen storage tanks and hydrogen piping to vent mast in case of system overpressure.

Each hydrogen pipe section between two segregation valves shall be provided with relief valve system connected to venting system.

Venting pipe shall be of single walled type and the material shall be in stainless steel suitable for hydrogen. Connections between pipes shall be welded.

8.2.8.3 Ventilation system

Ventilation system for the spaces dedicated to the storage and handling of hydrogen onboard, including PEMFC space, shall be designed to dilute and evacuate possible hydrogen losses in served spaces. Ventilation system shall also provide: the necessary process air to the PEMFC, extraction of FC exhaust gases and the sub-modules ventilation air. An effective extraction system shall be designed in order to grant requested air changes per hour for each served area. Both for extraction and supply system, attention must be paid to properly segregate ducting from different hazardous spaces.

Supply fans shall be designed in order to grant 30 air changes/hour, both to the served hazardous spaces and non-hazardous spaces.

All supply circuits shall be ducted and served by dedicated fans. Air distribution shall be provided both at the highest levels of the room and at ground-level. Air shall be locally distributed with the DIRIVENT System or other equivalent, which provides efficient air mixing and destratification.

Ventilation system shall provide also the necessary process and ventilation air to FC sub-modules. The air quantity, as well as air characteristics (temperature, filtration grade), shall be taken in accordance with FC supplier.

8.2.8.4 Extraction/exhaust system

The extraction system for non-hazardous areas (Hydrogen Storage Room, FC Room) shall be designed in such a way as to ensure separation between hazardous ducts and non-hazardous extraction.

The extraction systems for hazardous spaces shall consists of dedicated ducts with dedicated fans for the purpose of segregate each hazardous spaces from each other and from not-hazardous spaces. Air balance will be such to obtain under-pressure, in order not to allow the spreading of possible leakages.

The sub-modules ventilation air exhaust system shall consist of a dedicated duct for each pair of sub-modules (in accordance with FC supplier).

The FC exhaust gas extraction system shall consist of a dedicated duct with a dedicated (axial) extractor that convey gases directly into the funnel.

The FC exhaust gas extraction system shall consist of a dedicated duct with a dedicated (axial) extractor that convey gases directly into the funnel.

8.3 Stability evaluation

This section to verify the stability of the TransH2 project ship in her intact condition for the Regional Route. The stability of the ship has been verified in accordance with the IMO criteria for passenger ships as per the 2008 IS Code, by performing an analysis for different load conditions. All the stability requirements have been investigated and found to be in compliance with the referenced rules, as detailed in the following sections.

8.3.1 Stability analysis

The stability analysis was carried out using GHS software by Creative Systems Inc. Port Townsend, Wasington, USA, Licence No. NPI NavalProgetti20.4898DE306FAE. The hydrostatic model comprises displacement elements (green), sail elements (red), tank elements (dark green), and critical points (weathertight and flooding points). The following three-dimensional representation illustrates the hydrostatic model that was utilised.

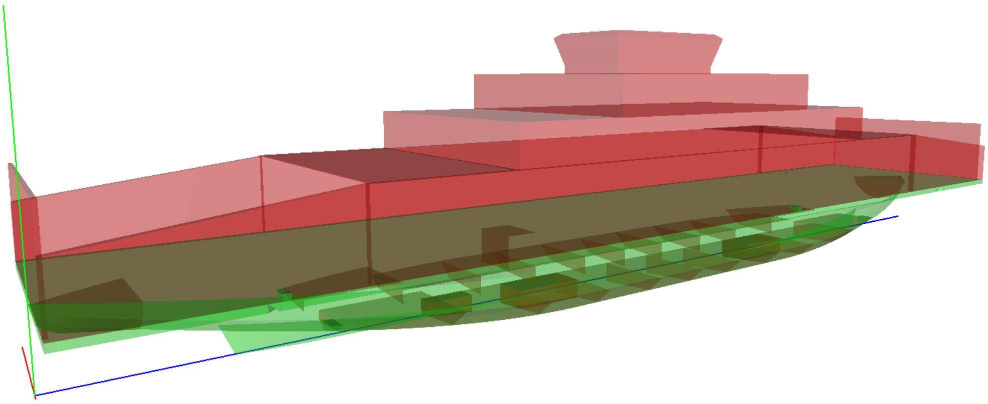


Figure 8-4: Regional Route ship hydrostatic model

8.3.2 Loading Conditions

Stability verification was performed for the most characteristic load conditions. In this case, the following load conditions were examined:

Load Condition n. 1: Ship with no cargo
Load Condition n. 2: Ship with light cargo (passengers & cars)
Load Condition n. 3: Ship with heavy cargo (passengers, cars & trucks)

Loading Conditions		**Weight**	**LCG**	**TCG**	**VCG**
			@ Aft PP	@ C.L.	@ B.L
		t	m	m	m
LC1- No Cargo		1 472	40.17	0.000	5.87
LC2- Light cargo		1 643	40.15	0.000	5.99
LC3 - Heavy Cargo		1 974	40.00	0.000	6.18

Table 8-4: Loading Conditions Summary

It should be noted that the condition of the ship at departure is very similar to that at arrival: the differences are negligible. Therefore, the loading cases analysed are valid for both the condition of the ship at departure and at arrival. The loading condition breakdown is offered in the following tables:

LC1- No Cargo								
Description	Quantity	Un.We.		Weight	LCG	TCG	VCG	FSM
					@ Aft PP	@ C.L.	@ B.L	
				t	m	m	m	tm
Lightship	1.00	1 442.00		1 442.00	40.00	0.00	5.93	0
Crew & provisions	1.00	2.00		2.00	40.00	0.00	10.60	0
Passengers	0.00	0.08		0.00	40.00	0.00	10.60	0
Consumables				27.82	48.76	0.12	0.76	57
Cars	0.00	1.60		0.00	40.00	0.00	6.00	0
Trucks	0.00	25.00		0.00	40.00	0.00	6.50	0
Trucks	0.00	44.00		0.00	40.00	0.00	6.50	0
Busses	0.00	25.00		0.00	40.00	0.00	6.50	0
Total				1 471.82	40.17	0.00	5.83	57
LC1- No Cargo				1 472	40.17	0.00	5.87	

Table 8-5: LC1 breakdown

LC2- Light cargo								
Description	Quantity	Un.We.		Weight	LCG	TCG	VCG	FSM
					@ Aft PP	@ C.L.	@ B.L	
				t	m	m	m	tm
Lightship	1.00	1 442.00		1 442.00	40.00	0.00	5.93	0
Crew & provisions	1.00	2.00		2.00	40.00	0.00	10.60	0
Passengers	480.00	0.08		38.40	40.00	0.00	10.60	0
Consumables				27.82	48.76	0.12	0.76	57
Cars	83.00	1.60		132.80	40.00	0.00	6.00	0
Trucks	0.00	25.00		0.00	40.00	0.00	6.50	0
Trucks	0.00	44.00		0.00	40.00	0.00	6.50	0
Busses	0.00	25.00		0.00	40.00	0.00	6.50	0
Total				1 643.02	40.15	0.00	5.96	57
LC2- Light cargo				1 643	40.15	0.00	5.99	

Table 8-6: LC2 breakdown

LC3 - Heavy Cargo								
Description	Quantity	Un.We.		Weight	LCG	TCG	VCG	FSM
					@ Aft PP	@ C.L.	@ B.L	
				t	m	m	m	tm
Lightship	1.00	1 442.00		1 442.00	40.00	0.00	5.93	0
Crew & provisions	1.00	2.00		2.00	40.00	0.00	10.60	0
Passengers	480.00	0.08		38.40	40.00	0.00	10.60	0
Consumables				0.00	48.76	0.12	0.76	57
Cars	32.00	1.60		51.20	40.00	0.00	6.00	0
Trucks	0.00	25.00		0.00	40.00	0.00	6.50	0
Trucks	10.00	44.00		440.00	40.00	0.00	6.50	0
Busses	0.00	25.00		0.00	40.00	0.00	6.50	0
Total				1 973.60	40.00	0.00	6.15	57
LC3 - Heavy Cargo				1 974	40.00	0.00	6.18	

Table 8-7: LC3 breakdown

Consumables & Ballast water								
Description	Volume	Fill	Sp.Gr.	Weight	LCG	TCG	VCG	FSM
					@ Aft PP	@ C.L.	@ B.L	
	m3		t/m3	t	m	m	m	tm
Fresh water	14.83	0.980	1.000	14.53	51.582	2.373	0.832	5.5
Ballast water	29.45	0.371	1.025	11.19	47.313	-3.078	0.623	46.3
Sewage	14.83	0.100	1.000	1.48	28.972	2.131	0.247	5.4
Hydrogen 350 bar	26.18	1.000	0.024	0.62	56.00	0.00	2.71	0.0
Total				27.82	48.76	0.12	0.76	57.18

Table 8-8: Consumables and ballast water

8.3.3 Lightship

The value of the lightship was calculated on the basis of a detailed load list and with the aid of the available database. The weight and center of gravity of the lightship were found to be:

Weight : 1442 t
LCG : 40.00 m from Aft Pp
TCG : 0.00 m off CL
VCG : 5.93 m above base line

Below is a summary table of the main items that make up the lightship:

LIGHTSHIP WEIGHT		Weight
		t
1	Steel Structure	1113.2
2	Hull completion	86.0
3	Hull Outfitting	57.0
4	Accommodation	58.5
5	HVAC and insulation	19.5
6	Piping	22.7
7	Electric equipment	34.0
8	ER equipment	43.3
9	Ship completion	7.8
Lighship weight		1442.0

Table 8-9: Lighship weight breakdown

8.3.4 General Stability Criteria

The ship shall comply with the IMO Intact Stability Code (IMO 2008 IS Code Part A Ch.2.2) as follows:

LIM (1) The area under the righting lever curve shall not be less than 0.055 metre-radians up to an angle of heel equal to 30°.

LIM (2) The area under the righting lever curve shall not be less than 0.09 metre-radians up to an angle of heel equal to 40° or the angle of down-flooding if this is less than 40°.

LIM (3) The area under the righting lever curve between the angles of heel of 30° and 40° or between 30° and the angle of down-flooding if this angle is less than 40°, shall not be less than 0.03 metre-radians.

LIM (4) The righting lever shall be at least 0.20m at an angle of heel equal to or greater than 30°.

LIM (5) The maximum righting lever shall occur at an angle of heel not less than 25°. If this is not practicable, alternative criteria may be applied.

LIM (6) The initial metacentric height GM0 shall not be less than 0.15m.

8.3.5 Alternative Stability Criteria

The following equivalent criteria should be applied where the ship's characteristics render compliance with IMO 2008 IS Code Part A Ch.2.2.3 impracticable, i.e. when the maximum righting lever shall occur at an angle of heel less than 25°:

LIM (1): the area under the curve of righting levers (GZ curve) should not be less than 0.07 metre-radians up to an angle of 15° when the maximum righting lever (GZ) occurs at 15° and 0.055 metre-radians up to an anglc of 30° whcn thc maximum righting lever (GZ) occurs at 30° or above. Where the maximum righting lever (GZ) occurs at angles of between 15° and 30°, the corresponding area under the righting lever curve should be: 0.055 + 0.001 (30°-AngGZmax) metre-radians;

LIM (2): the area under the righting lever curve (GZ curve) between the angles of heel of 30° and 40°, or between 30° and <pr if this angle is less than 40°, should be not less than 0.03 metre-radians;

LIM (3): the righting lever (GZ) should be at least 0.20 m at an angle of heel equal to or greater than 30°;

LIM (4): the maximum righting levcr (GZ) should occur at an angle of heel not less than 15°;

LIM (5): the initial transverse metacentric height (GM0) should not be less than 0.15 m;

8.3.6 Weather criterion (2008 IS CODE)

The ability of a ship to withstand the combined effects of beam wind and rolling should be demonstrated for each standard condition of loading, with reference to figure below, as follows:

1. The ship is subjected to a steady wind pressure acting perpendicular to the ship's centreline which results in a steady wind heeling lever (lw1);
2. From the resultant angle of equilibrium (Fi0), the ship is assumed to roll owing to wave action to an angle of roll (Fi1) to windward;
3. The ship is then subjected to a gust wind pressure which results in a gust wind heeling lever (lw2);

- LIM (27) under these circumstances, area "b" should be equal to or greater than area "a".

- LIM (28) the angle of heel under action of steady wind (Fi0) should not exceed 16° or 80% of the angle of deck edge immersion, whichever is less.

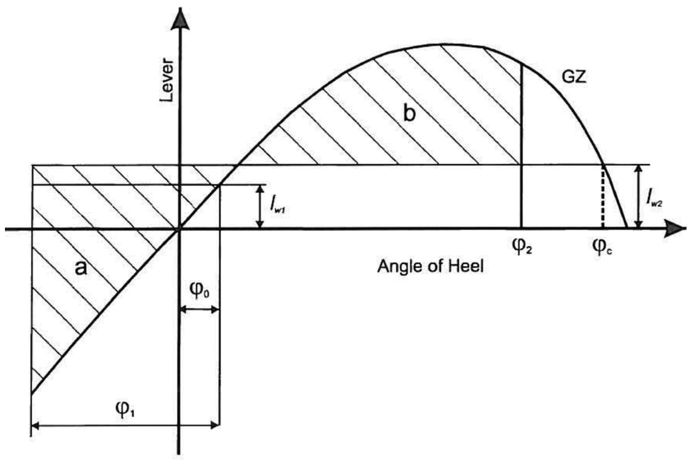


Figure 8-5: IMO Weather Criterion

The angles in figure are defined as follows:

FI0 = angle of heel under action of steady wind

FI1 = angle of roll to windward due to wave action

FI2 = angle of roll downflooding or 50° or FIc , whichever is less, where:

FIf = angle of heel at which openings in the hull, superstructures or deck-houses which cannot be closed weathertight immerse.

FIc = angle of second intercept between wind heeling lever (lw2) and GZ curve.

8.3.7 Passenger Ship Stability Criteria

As per IMO 2008 IS Code Part A Chapter 3.1, the passenger ships shall comply with the requirements listed above and in addition shall comply also with the following additional criteria, as per IMO 2008 IS Code Part A Chapter 3.1.1.

LIM (31): the angle of heel on account of crowding of passengers to one side shall not exceed 10

LIM (32): the angle of heel on account of turning shall not exceed 10° when calculated using the following formula:

Mr=0.200·(Vs^2)/L_wl ·Δ·(KG-d/2)

where:

Mr = heeling moment (kNm)

Vs = service speed (m/s)

LWL = length of ship at waterline (m)

Δ = displAcement (t)

d = mean draught (m)

KG = height of centre of gravity above baseline (m)

8.3.8 Stability Analysis Results

The following tables show the results of the stability analysis, which demonstrate that all stability requirements are satisfied.

LC	Displ	Draft	Trim	Heel
		@ B.L.	@ PP	
			+Aft	+Stbd
	t	m	m	deg
LC1	1 469	2.44	0.01	0.00
LC2	1 640	2.63	0.02	0.00
LC3	1 971	2.98	0.10	0.00
Max	1 971	0.00	0.00	0.00
Min	1 469	2.44	0.01	0.00
Status				

Table 8-10: Loading Conditions results

LC	LIM (1)	LIM (1)	LIM (2)	LIM (3)	LIM (4)	LIM (5)			LIM (27)	LIM (28)	LIM (31)	LIM (32)
	Area	Area	Area	RA	Angle	GMT	Area	Area	Weather	Steady wind	Crowding	Turning
	0°-Max°	0°-Max°	30° - 40°	30deg	@ RA Max		0° - 30°	0° - 40°	A2/A1	Heel	2.89	0.67
	Attained	Requested	> 0.030	> 0.20	>15	> 0.15	> 0.055	> 0.090	>1	<16°;80%DI	<10	<10
	rad.m	rad.m	rad.m	m	deg	m	rad.m	rad.m	-	deg	deg	deg
LC1	0.418	0.061	0.213	1.641	24.5	4.79	0.582	0.795	1.45	2.1	2.7	0.5
LC2	0.353	0.061	0.138	1.412	23.6	4.16	0.522	0.660	1.43	2.1	2.7	0.5
LC3	0.248	0.063	0.037	0.972	21.6	3.26	0.414	0.451	1.22	2.2	2.9	0.7
Max	0.418	0.063	0.213	1.641	24.5	4.79	0.582	0.795	1.45	2.2	2.9	0.7
Min	0.248		0.037	0.972	21.6	3.26	0.414	0.451	1.22	2.1	2.7	0.5
Status	Passed		Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed

Table 8-11: Loading Conditions results

8.4 Power prediction

This section presents preliminary calculations relating to the power forecasts for the bidirectional, hydrogen-powered ferry operating on the Split-Supetar Regional Route. The results reported below have enabled to assess the propulsive power required by the ferry and calculate the number of fuel cell stacks needed to power the ship.

Some information is also provided for the Tronchetto-Lido route. However, this route has a much lower impact in terms of resistance, installed power and energy autonomy because it is shorter and travelled at lower speeds. Therefore, the Split–Supetar route will generally be used as a reference point in the Regional Route analysis.

8.4.1 Ship main characteristics

The propulsion power estimation has been predicted taking into account the ship main characteristics as listed in the following Table 8-12:

Description	Symbol	Value	Unit
Length Overall	LOA	80.40	[m]
Length at Waterline	LWL	78.60	[m]
Max. Breadth	B	17.00	[m]
Breadth at Waterline	BWL	~ 15.00	[m]
Depth	H	5.00	[m]
Max Draft / Power estimation draft	T	3.20	[m]
Speed	V	11.0	[kn]
Number of propellers		2	
Total Propulsion Power @100% MCR	Pmax	2x500 = 1000	[kW]
Class Notation	✠ 100A1 – Ro-Ro Passenger Ferry; specific coastal service		

Table 8-12: Ship main characteristics – Regional Route Split - Supetar

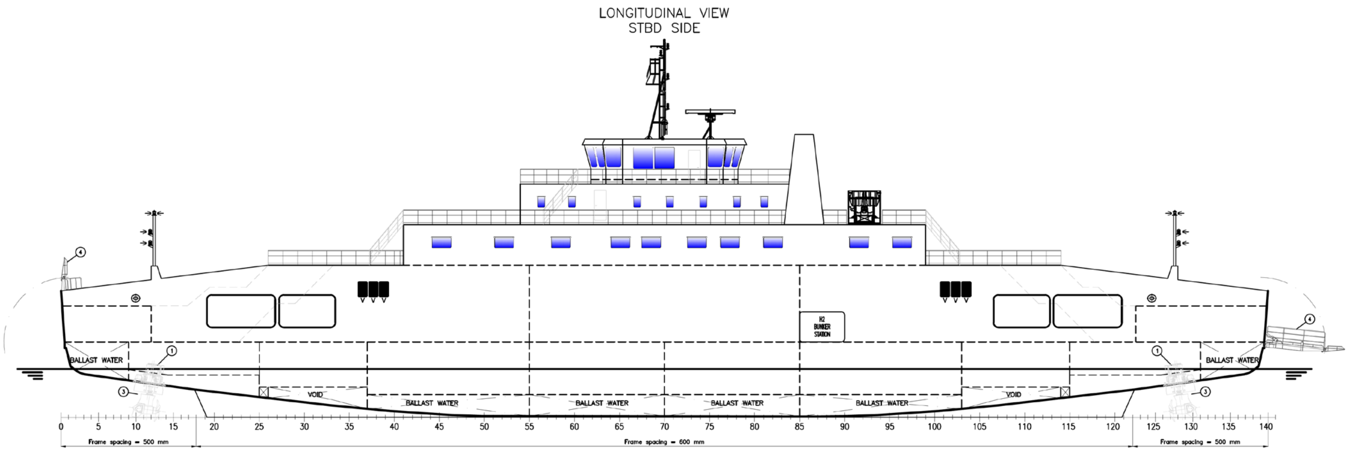


Figure 8-6: Ship longitudinal view

8.4.2 Description of power plant

The propulsion units deliver a maximum power of 1000 kW (2x500), which is sufficient to ensure a speed of 11 knots in open water conditions (PB = 868 kW), running at approximately 87% MCR.

The twin-screw configuration consists of two Z-drive thrusters, each with a 1.45-metre-diameter propeller, connected to electric propulsion motors. These motors are powered by electricity produced by fuel cells, with battery packs providing additional power during peaks. This configuration enables the ship to manoeuvre well in restricted waters and when approaching the dock. The propellers are fixed-pitch (FPP) and are positioned at the bow and stern of the ship.

For the Tronchetto–Lido route, the above data are reduced to 2 x 175 kW of installed propulsion power to ensure a speed of 6 knots (PB = 285 kW @ 81% MCR, with a propeller diameter of 1.2 m).

8.4.3 Resistance analysis

Resistance predictions were carried out using NavCad software by HydroComp Inc. , New Hampshire, USA, Licence No. 18.02.0071.0156.V0691. The resistance curves for the ferry are shown in the following figure for both the Italian Regional Route Tronchetto–Lido and Croatian Regional Route Split–Supetar.

The two routes differ in terms of environmental conditions, as defined in Ref. [15] D.2.1.3. These differences are evident in the wind speed, wave height and bathymetric profile, all of which modify the relative components of resistance to forward motion:

Croatian Regional Route: Split-Supetar

- Wind speed: 10.5 kn
- Significant wave height: 1.00 m (*)
- Sea depth (assumed constant): 30 m

Italian Regional Route: Tronchetto-Lido

- Wind speed: 20.0 kn
- Significant wave height: 1.00 m (*)
- Sea depth (assumed constant): 10 m

(*) Report Ref. [15] D.2.1.3 indicates higher values for significant wave height, ranging between 1 and 4 m for the Venice route and up to 1.5 m for the Split route. However a wave with Hsig 1 m was assumed in the resistance calculations because it is more consistent with a sustainable operating limit for navigation at the expected speed.

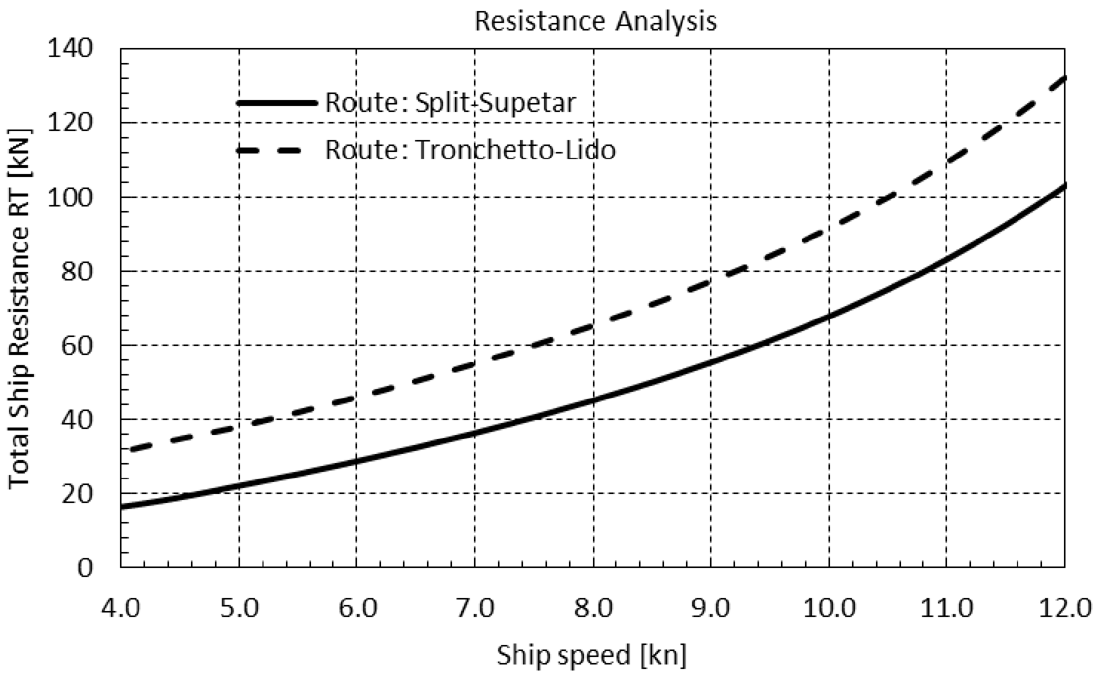


Figure 8-7: Total Ship Resistance RT [kN] – Regional Route

8.4.4 Power analysis

Within the TransH2 project, the result relating to propulsion is of fundamental importance. This is not so much because it determines the choice of engine size to be installed, but rather because it provides information on the ship's energy balance. Propulsion power accounts for approximately 78% of the energy required to operate the ferry, which obviously affects the amount of fuel that must be stored on board to ensure a day's autonomy.

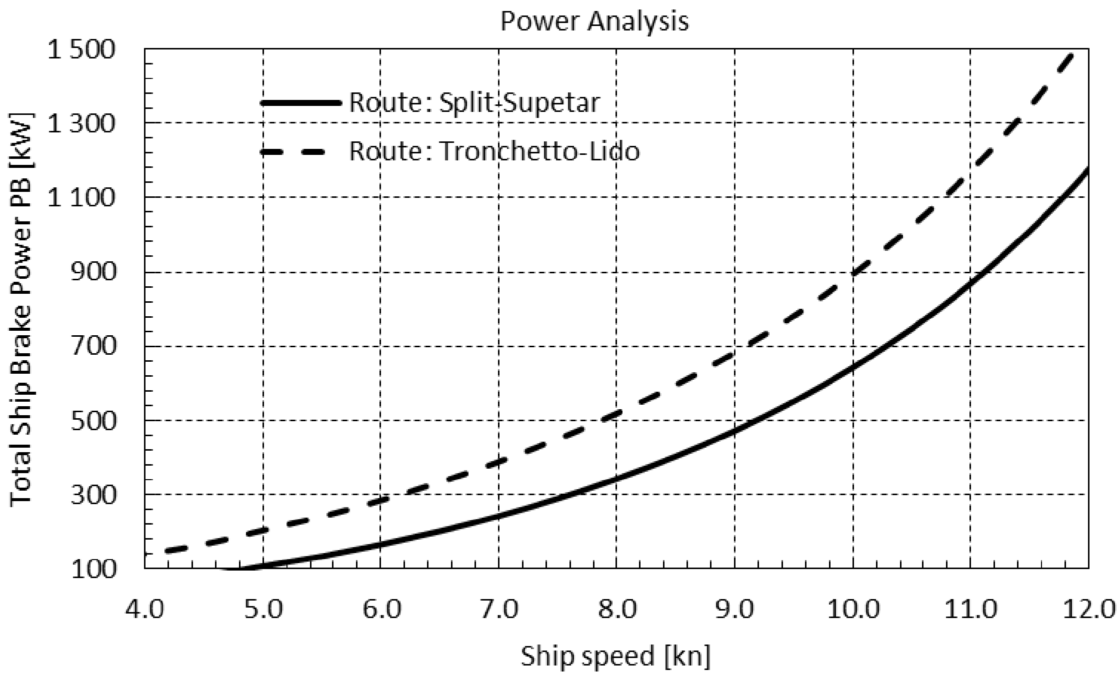


Figure 8-8: Total Ship Brake Power PB [kW] – Regional Route

At a speed of 11 knots (Split Route), the required brake power PB is 868 kW, corresponding to 87% of the maximum power deliverable by the propulsion systems (87% MCR).

With regard to the Venetian route, the aforementioned data is reduced to a ship speed of 6 knots (due to the Venetian channel speed regulation), with the required brake power PB set at 285 kW. This corresponds to 81% of the maximum power deliverable by the propulsion systems (81% MCR).

8.5 Bunkering

8.5.1 Gaseous Hydrogen Bunkering from Shore: Procedures and Safety Overview

Bunkering compressed gaseous hydrogen from a fixed shore-based installation to a ship requires careful planning, dedicated high-pressure equipment, and strict operational control. H_2 transfer operations involve hydrogen at elevated pressures, typically up to 350 bar or 700 bar, with associated hazards related to rapid gas release, jet dispersion, and ignition.

Shore-to-ship H_2 bunkering must comply with flag-state requirements, classification society rules, and local port authority regulations. This document provides an overview of shore-to-ship H_2 bunkering procedures, focusing on safety systems, regulatory compliance, and operational best practices. It is intended as a technical reference for ship and terminal design, port interface definition, and hazard identification studies (HAZOP/QRA).

The shore-based H_2 bunkering station shall be located in the port where the ship will remain moored during the night stay.

For detailed discussion on shore-based H_2 bunkering station see Ref. [19] and [20].

8.5.2 Bunkering Regulatory Framework and Standards

8.5.2.1 International and Flag-State Framework

The IMO IGF Code does not yet include prescriptive requirements for hydrogen bunkering operations. Approval of H_2 bunkering arrangements is therefore generally achieved through the alternative design process, supported by flag-state acceptance and risk-based justification.

Flag administrations typically require:

- A documented H_2 bunkering safety concept
- Hazard identification and risk assessment (HAZID/HAZOP)
- Quantitative Risk Assessment (QRA) to define safety and exclusion zones
- Emergency shutdown and response philosophy

8.5.2.2 Classification Society Requirements

Classification societies such as Lloyd’s Register, DNV, and ABS provide technical requirements for gaseous hydrogen fuel systems and bunkering interfaces. These rules typically require:

- Open-deck or well-ventilated bunkering stations on board
- Design approval of high-pressure hydrogen piping, hoses, valves, and connectors
- Hydrogen dispersion and jet fire risk analysis
- Redundant isolation and emergency shutdown systems
- Hazardous area classification in accordance with ATEX / IECEx (Group IIC)

Bunkering stations are generally required to be located away from accommodation spaces and critical ship systems, with unobstructed vertical dispersion paths for released gas.

8.5.2.3 Port Authority and National Requirements

To allow H_2 bunkering from shore installations, ports typically impose port-specific operational requirements, including:

- Approval of terminal layout and safety systems
- Site-specific safety distances based on QRA
- Coordination with local fire and emergency services
- Issuance of a bunkering permit for each operation or campaign

First-of-a-kind or early-stage H_2 bunkering operations may require additional supervision by port authorities and emergency responders.

8.5.3 Shore-to-Ship H_2 Bunkering Configuration

8.5.3.1 General Arrangement

In a shore-to-ship configuration, hydrogen is supplied from a fixed hydrogen production or storage facility via high-pressure piping to a quay-side bunkering point. Transfer to the ship is performed using:

- High-pressure hydrogen-rated flexible hoses or articulated loading arms
- Dry-break couplings and emergency release systems
- Pressure control and metering equipment located on shore

The ship is securely moored at the berth, and the bunkering station is located on an open deck with direct ventilation to atmosphere.

The number of connections (loading arms) should be sufficient to guarantee the necessary H2 flow rate.

8.5.4 Shore-to-Ship H_2 Bunkering Procedure

8.5.4.1 Pre-Bunkering Preparation

Before bunkering commences:

- A Joint Bunkering Operation Plan is agreed between ship and terminal operators
- Pre-transfer safety checklists are completed
- Communication channels and emergency signals are verified
- Shore and ship emergency shutdown (ESD) systems are function-tested
- A safety and exclusion zone is established on the quay and waterside

Non-essential personnel, vehicles, and ignition sources are removed from the controlled area.

8.5.4.2 Connection and System Verification

- High-pressure hoses or loading arms are connected to the ship's bunker manifold using dry-break couplings
- Electrical bonding and grounding between ship and shore are confirmed
- The transfer line is pressure-tested and leak-checked, typically using inert gas
- Hydrogen gas detectors at the ship–shore interface are verified operational

Only after successful verification, the system is declared ready for hydrogen bunkering.

8.5.4.3 Transfer Operation

Hydrogen transfer is initiated at a controlled rate to confirm system integrity. Depending on the installation, transfer is driven by:

- Pressure equalization between shore storage and ship tanks, and/or
- Shore-based hydrogen compressors

During transfer:

- Pressure, temperature, and flow are continuously monitored on both ship and shore
- Hydrogen gas detection systems provide continuous leak monitoring
- Transfer is performed as a fully closed operation, with no routine venting

Shore and ship ESD systems are interlinked so that activation on either side immediately isolates the transfer and stops hydrogen flow.

8.5.4.4 Completion and Disconnection

When the required pressure or quantity is reached:

- Transfer is stopped and isolation valves are closed
- The transfer line is depressurized to a safe level, normally back into the shore system
- Hoses or loading arms are disconnected using dry-break couplings

A post-bunkering check confirms all systems are secured and documentation completed.

8.5.5 Safety Measures and Equipment

8.5.5.1 Emergency Shutdown Systems

- Fast-acting automatic isolation valves on both shore and ship sides
- Interlinked ESD systems tested prior to bunkering
- Fail-safe, normally closed valve design

8.5.5.2 Gas Detection and Monitoring

- Fixed hydrogen gas detectors at the ship–shore interface, manifolds, and vent outlets
- Alarm thresholds set well below the lower flammability limit
- Portable hydrogen detectors carried by operational personnel

8.5.5.3 Hazardous Area Classification

- Defined Zone 1 and Zone 2 hazardous areas around bunkering equipment. For instance, the radius around couplings and vent outlets will be Zone 1 (high probability of H_2 during transfer) and a further perimeter Zone 2 (less likely, only in abnormal conditions).
- All electrical and instrumentation equipment must be explosion-proof (EX-rated) certified for hydrogen service (Group IIC)
- Strict control of ignition sources and static electricity

8.5.5.4 Personnel Training and PPE

Personnel involved in H_2 bunkering are trained in hydrogen properties, high-pressure system risks, and emergency response. During operations, personnel wear flame-resistant clothing, eye protection, and suitable communication equipment. A designated safety officer typically supervises the operation.

8.5.5.5 Operational Restrictions and Controls

- Suspension of bunkering during electrical storms or unsafe weather conditions
- Restriction or suspension of passenger movement during transfer
- Prohibition of hot work and other fuel transfers during H_2 bunkering
- Enforcement of quay-side and waterside exclusion zones

8.5.5.6 Emergency Response

Emergency response measures include:

- Pre-positioned firefighting and gas detection equipment
- Clearly defined evacuation routes and muster points
- Tested emergency shutdown and communication procedures
- Coordination with port emergency services and fire brigade

8.6 Energy Balance

8.6.1 General

This section studies the ship's energy balance in order to assess the amount of hydrogen (H2) that will be carried on board at the start of an operating day (the starting conditions at the first trip departure). The determined amount of H2 will be stored in cylinders where the gas will be compressed to 350 bar.

Regarding the number of refuelling operations to be carried out each day, the arrangement of the cylinders, and other aspects, reference has been made to Doc. D.2.1.4 'Option analysis for the introduction of hydrogen-fuelled solutions in three use cases'.

8.6.2 H2 energy reserve

The H2 energy reserve ER has been evaluated according to the following basic assumption:

H2ER = [Pn*Tn + Pp*Tp] * n

where:

H2ER: the energy consumed in one operative day, kWh
Pn: the mean power (propulsion & auxiliaries) developed during navigation, kW
Tn: the time for one trip navigation, h
Pp: the mean power (auxiliaries) developed during port stay, kW
Tp: the time for one port stay, h
n: the number of trip in a day

The inner net volume for each cylinder has been evaluated according to the following basic assumption:

VOLcyl = H2vol / NR / NC

where:

VOLcyl: the internal volume of one cylinder
H2vol: the H2 @ 350 bar volume consumed in one operative day
NR: the number of refuellings in a day
NR: the number of cylinders

In order to calculate the H2 @ 350 bar volume consumed in one operative day, the following aspects must also be taken into consideration, as the fuel cells (FC) efficiency 40% (conservative assumption retrieved from FC manufacturer), an overall electric efficiency 98%, a fuel contingency of +30% (assumed for worst weather conditions, longer port time, route change, ecc.), heel 5 barg, H2 net heat value 33.31 kWh/kg (from National Institute of Standards and Technology – Refprop), H2 density 23.72 kg/m3 (at gaseous phase, 293 K, 350 barg), H2 density heel 0.49 kg/m3 @ 293 K, 5 barg.

The H2 energy reserve shall be stored in 350 bar composite cylinders with the following characteristics:

Croatian Regional Route Split-Supetar:	
Mean power during sailing, kW:	988
Mean power during port stay (*), kW:	300
H2 consumption on an operative day, kg/day:	1216
No. of refuelling in an operation day:	2
Cylinder length, m:	5.7
Cylinder outer diameter, m:	1.11
Cylinder net inner volume, litres:	3740
Number of cylinders:	7
One cylinder (empty) weight, kg:	2287
H2 weight in one (full) cylinder, kg:	89
Time for one refuelling(**), h	~ 3.1

Italian Regional Route Tronchetto-Lido:	
Mean power during sailing, kW:	321
Mean power during port stay (*), kW:	90
H2 consumption on an operative day, kg/day:	464
No. of refuelling in an operation day:	2
Cylinder length, m:	5.7
Cylinder outer diameter, m:	1.05
Cylinder net inner volume, litres:	3330
Number of cylinders:	3
One cylinder (empty) weight, kg:	2076
H2 weight in one (full) cylinder, kg:	79
Time for one refuelling(**), h	~ 1.8

(*) The power output during the port stay must not fall below 25% of the FC nominal power.
(**) Two refuelling connections, 144 kg/h each, working in parallel. Preparation time (30min) and disconnection time (30min) were both taken into account.

The quantities of hydrogen to be stored on board deviate marginally from the assessment initially completed in in Ref. [16] D.2.1.4. This is a consequence that the present report conducted a deeper analysis of the power requirements during navigation and port stops, as well as for the various efficiencies and contingency margins that should be maintained.

8.6.3 Battery pack capacity

In terms of battery pack capacity, the 'safe return' feature was designed to enable the ship to return to the nearest port in the event of a total failure of the FC system. This feature provides sufficient capacity for a reduced-speed journey (approximately 6 knots) with a maximum journey length of half the route. The energy required for the 'safe return' battery pack is:

- For the Split-Supetar regional route: 245 kWh
  corresponding to approx. 380 kWh nominal capacity (*)

- For the Tronchetto-Lido regional route: 114 kWh
  corresponding to approx. 175 kWh nominal capacity (*)

(*) considering fluctuations due to maneuvering consumption, 15% DoD and 20% EoL degradation

In addition to the above, an adequate energy reserve must be added for normal operation of the FC.

8.7 Preliminary electric system design

The basic configuration of the electrical power plant is given in the Principle one line diagram.

The main el. power plant consist of six PEM Fuel Cells of 200 kW each. The power cells are working together with a battery bank. Four battery stacks of abt. 175 kWh each are foreseen.

The total capacity of the el. power sources are:

- Fuel cell total nominal power: 1200 kW
- Batteries total nominal capacity: 700 kWh

The Fuel cells as well as the batteries are connected to the Main DC Switchboard trough a DC/DC converters. The busbars of the Main DC switchboard can be divided in two parts by mean of an isolating switch, in case of failure in one part of the switchboard. In normal operation of the ship, the isolating switch is always closed.

From the Main DC switchboard are directly supplied the two DC/AC inverters with variable frequency outputs for supply of the two propulsion motors.

A shore connection box for connection to the shore based DC charging station for battery charging during the night is foreseen. During charging, the shore battery charging station will be interfaced with the ship Power Management System, in order to control the charging.

The ship auxiliaries as well as the hotel loads will be supplied with 3x400V, 50 Hz, and 230V, 50 Hz. For this purpose, a 3x400 V 50 Hz switchboard will be installed. The switchboard will be supplied from the Main DC switchboard trough a two DC/AC inverters. One inverter will be in operation, the other in stand-by. Two transformers 3x400/3x230V, 50 Hz are provided for supply of the 230V section of the AC switchboard.

Emergency switchboard 24V DC will be provided, supplied in normal condition from the 400V AC switchboard through a rectifier. In case of black-out, the emergency battery 24 VDC will supply the emergency consumers. From the Emergency switchboard should be supplied also the Fuel cell and Battery stack safety systems.

Operating modes

The following operating modes can be distinguished:

- Sailing: The ship is to be capable of sailing at service speed of 11kn
- Manoeuvring during mooring operation
- Moored with car and passenger loading/unloading
- Moored during the night – no operations
- Safe return to port in case of Fuel Cells failure

During normal sailing, as well as during mooring operations, the power demand will be covered with the Fuel Cells, while the batteries will cover eventual peaks loads.

When the ship is moored with car and passenger loading/unloading , the main power demand come from the auxiliaries plus the hotel loads. The load is still covered with the Fuel cells. If the actual power demand is below the Fuel cell minimum power, the Power Management System will ensure to increase the load of the fuel cells by send part of the energy to charge the batteries. In this way, it is ensured that the Fuel cells will always operate in the range above the minimum power.

During the night, when the ship is moored with no operation, the ship DC power plant will be connected to a shore based DC charging station, in order to recharge the batteries.

In the case of hydrogen Fuel cells system failure and consequently Fuel cells shut-down, the ship should be able to return to port with battery power only. According to the energy balance for safe return to port, calculating half of the route length and assumed speed of 6 kn, the required battery energy for safe return to port is about 380 kWh. That's mean that the Power Management System should maintain the battery charged during navigation at least at 55% of nominal capacity. In this way, all the time during navigation, the battery stored energy will be sufficient for safe return to port with batteries only.

The preliminary one-line diagram is shown in the picture below.

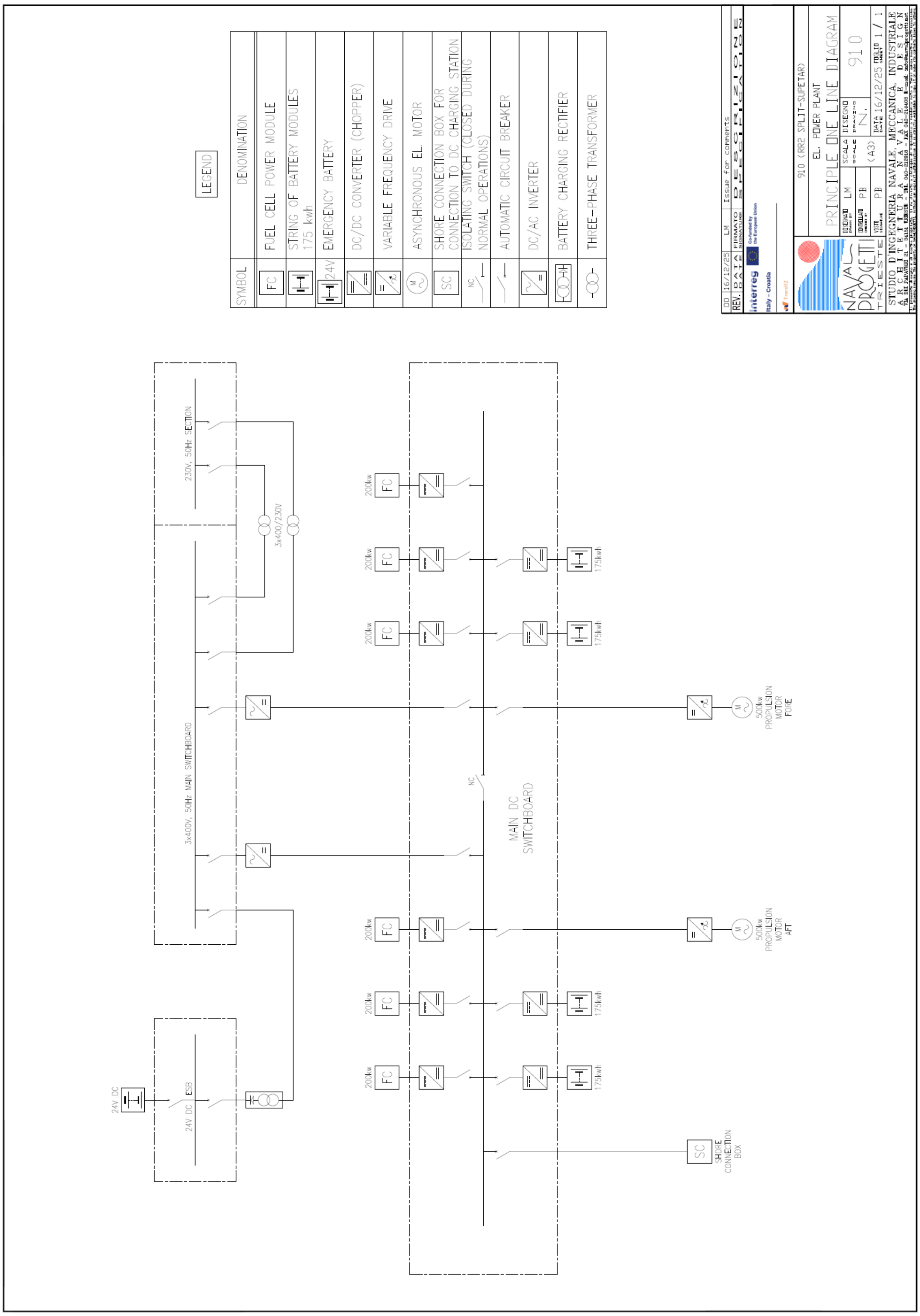


Figure 8-9: Preliminary electric one-line diagram

8.8 Hazardous area plan

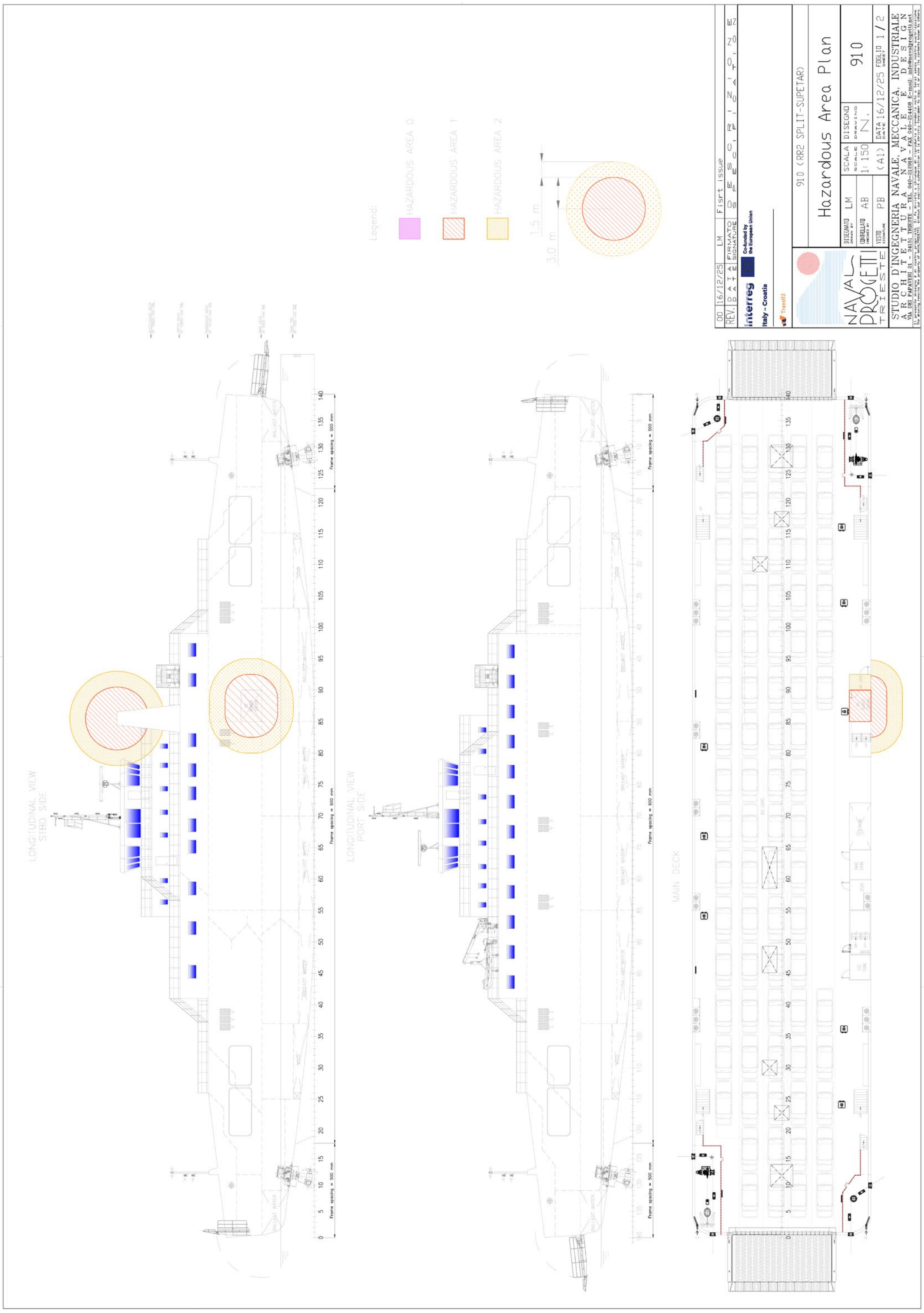


Figure 8-10: Hazardous Area Plan (1)

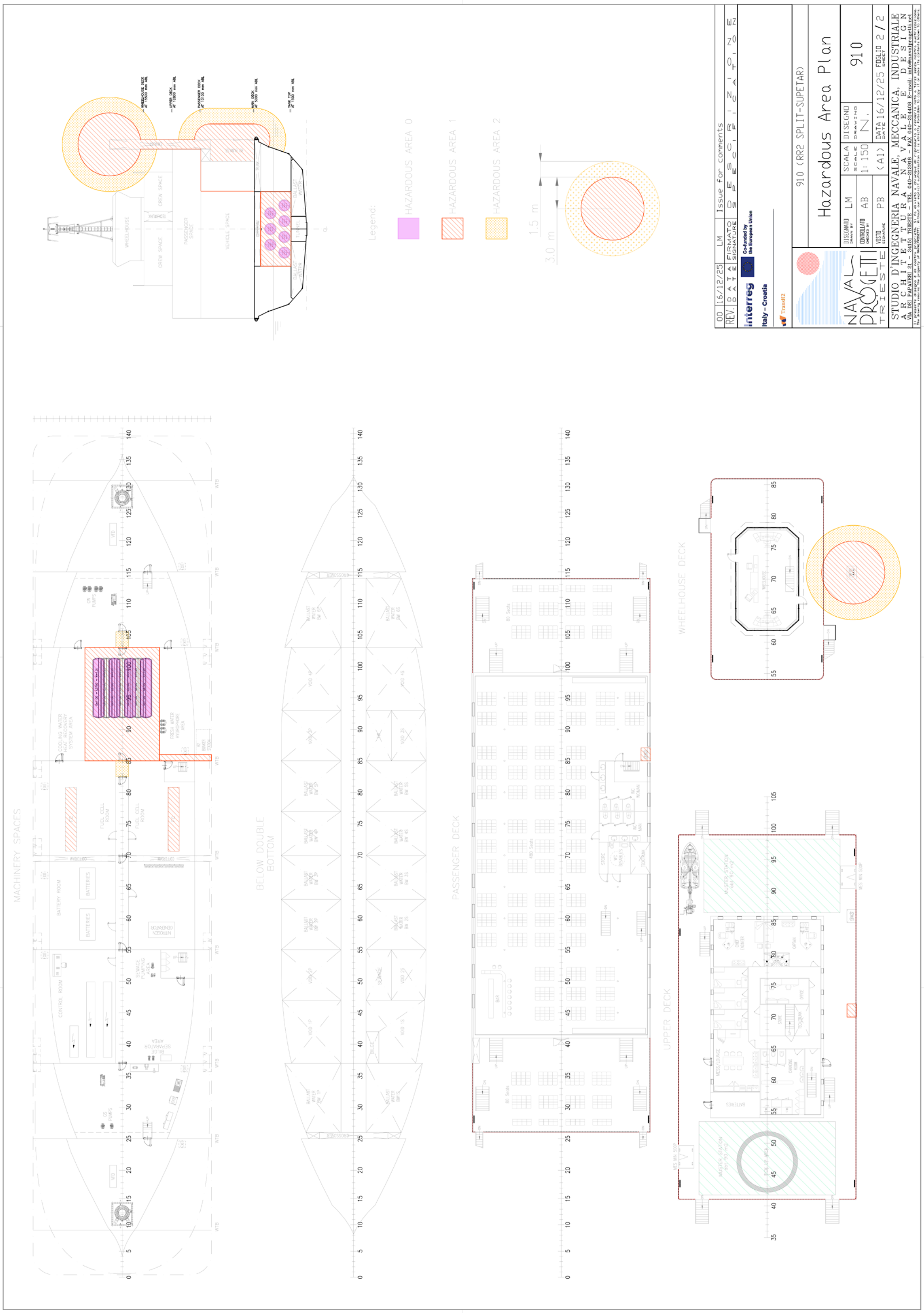


Figure 8-11: Hazardous Area Plan (2)

8.9 Emergency shut down philosophy

The scope of this document is to establish basic requirements and basic functions to be adopted in the design and development of the Emergency Shut-Down (ESD) system onboard the ship provided with H2 Fuel cell and battery power system.

The basic functions of the ESD system described in this document should be discussed and verified during Risk analysis, HAZID and HAZOP analysis and consequently modified/completed.

8.9.1 Design Criteria

The following main design criteria should be followed:

- the ESD system should be completely independent from other systems; only information exchange between ESD and other safety systems should be established.
- It shall be possible to carry out a manual emergency shutdown from the following locations as applicable:
    - wheelhouse
    - FC control room;
    - adjacent to the exit and inside of fuel cell rooms.
    - adjacent to the exit and inside the hydrogen storage room;
    - adjacent to the exit and inside the battery room
- The manual activation buttons shall be protected against unintended operation.
- Cables shall be fire resistant and adequately mechanical protected.
- When an emergency shutdown has been activated, automatic attempts of re-starting the machinery/equipment shall be deactivated for as long as the shut-down is activated.
- The emergency shutdown system shall be so constructed that it will fail to the conditions which are safest for the ship both in the event of signal failure and power supply failure. In case of ESD failure the system should not perform any automatic actions except failure alarm.
- The emergency shutdown system shall be protected against common mode failures and physical damage. This may be achieved by separation of equipment and appropriate physical and electrical division of the system.
- There shall be two sources of power for operation of the emergency shutdown system. In the event of failure in the regular power supply, the reserve power supply shall automatically take over.

8.9.2 ESD system architecture

The H2 storage, fuel cell and batteries ESD system consists of field mounted sensors and pushbuttons, ESD valves, dampers, trip relays, status indicators, system logic for processing of incoming signals, alarm and HMI units. The system should be able to process input signals and activate outputs in accordance with the cause and effect chart to be defined for the installation.

The ESD system shall be operated from operator stations located in Wheelhouse and FC Control Room.

The ESD system shall operate as an independent system and shall be interfaced to the other Safety systems hardwired or by redundant serial link. The ESD system actuators loop shall be normally de-energised system with loop monitoring and alarm in ECR.

The ESD system shall have hardwired interfaces for important functions, such as activation of shut down valves.

The ESD system shall be interfaced with other ship systems, eighter hardwired or via redundant serial link, as follows:

- Automation system, particularly with power management system
- Gas detection system
- Fire detection system
- Ventilation system
- H2 valves control system
- Fuel cell control and monitoring system
- Batteries control and monitoring system

Push buttons for manual shut down shall be installed on the locations as mentioned above.

There are three basic automatic functions of the Emergency shutdown system, namely:

- Shut off of hydrogen supply to Fuel cells
- Shut down of the fuel cell system
- ESD of the battery system

As a manual shutdown can be unreliable and can lead to a large gas cloud before the shutdown is performed, isolation and shutdown should be initiated automatically for hydrogen systems.

8.9.3 Gas detection

A permanently installed gas/vapour detection system shall be provided for:

- hydrogen storage room
- fuel cell spaces
- air locks
- battery room
- other enclosed spaces where gas may accumulate.

The detection systems shall continuously monitor for gas/vapour.

Detection systems for flammable products capable of measuring gas/vapour concentrations in the range 0-100% LEL shall be used.

The number of detectors in each space shall be considered taking size, layout and ventilation of the space into account, and each space shall be covered by sufficient number of detectors to allow for voting.

The detectors shall be located where gas/vapour may accumulate and/or in the ventilation outlets.

Gas/vapour detection in a fuel cell spaces and H2 cylinders space when two self-monitored detectors indicate a gas or vapour concentration of 40% LEL shall shut-down the affected fuel cell power system and disconnect ignition sources and shall result in automatic closing of all valves required to isolate the leakage. This will require that valves in the primary fuel system supplying gaseous fuel to the fuel cell space shall close automatically.

Means of manual emergency shutdown of fuel supply to the fuel cell space and de-energizing the ignition sources shall be provided inside a fuel cell space, in the FC control room and from the navigation bridge. The activation device shall be arranged as a physical button, duly marked and protected against inadvertent operation. The manual shutdown shall be handled by the ESD system and be arranged with loop monitoring.

8.9.4 Ventilation

There are basically three ventilation systems:

- Ventilation of H2 storage compartment
- Ventilation of the fuel cell rooms
- Ventilation of the battery room

Reduced ventilation below the required capacity shall be alarmed.

In order to verify the performance of the ventilation systems, a detection system of the ventilation flow and a monitoring system of the negative fuel cell space pressure is required. A running signal from the ventilation fan motor is not sufficient to verify performance.

Loss of ventilation in a fuel cell space shall result in an automatically shut down of the fuel cell by process control within a limited period of time. The period for the shut down by process control shall be considered on a case by case basis based on the risk analysis.

After the period has expired a safety shut down shall be carried out. The ESD of the H2 fuel cell system shall be automatically initiated also in case of loss of ventilation in the H2 storage compartment as well as in the fuel cell room.

8.9.5 Fire detection

An overall fire and explosion safety philosophy and strategy needs to be developed.

A fire detection system needs to consider the properties of hydrogen flames and use appropriate flame detectors, such as IR detectors.

In case of fire detection, the ESD system should also stop the ventilation so that the air supply to the rooms/cells is halted.

Fire detection is to be arranged such that the activation of any fire detectors in, or adjacent to hazardous areas or spaces containing gaseous, cryogenic liquid, toxic, corrosive or liquid fuels with a flash point below 60°C will automatically shut down any part of the fuel cell power system within or adjacent to such spaces. (LR Rule proposal 2020/01).

The lithium battery space is to be fitted with suitable fixed detectors in accordance with manufacturer's recommendations and which are capable of providing early identification of a fire or thermal runaway condition. Early identification is to include high cell temperature or detection of electrolyte solvent vapours and a combination of smoke and heat detectors.

When activated, the fire detection system is to initiate an alarm to the relevant control stations and on the navigating bridge and is to initiate the automatic isolation of electric systems within the lithium battery space, except as described below, and activate the fixed fire-fighting system.

In the event that a fire or thermal runaway condition is identified, the battery monitoring system is to initiate protective features such as automatic safe isolation of the batteries. Ventilation necessary for extraction of gases, active cooling systems, and thermal/safety monitoring and alarm are to be continued prior to, during and after an overheating or fire event. Failure of the monitoring system is to be alarmed to the ship's safety system and is to result in the battery system automatically reverting to a defined safe state.

8.9.6 Fuel cell control and monitoring system

If limit values determined for the FC control process, e.g. temperature, pressure, or voltage, which may lead to hazardous situations, the fuel cell power system is to be automatically shut down and interlocked by an independent protective device.

As the FC are divided in two groups of 600 kW each, the shutdown of one group of cells shall not cut the fuel supply to the other group of cells.

In any case the ESD system should inform the Power Management System if one or all group of cells are shut down, in order that the PMS will reduce the ship power plant load or transfer the load to the batteries only, in case that all FC are out of operation.

Typical monitoring parameters of the fuel cell that should be considered:

- cell voltage
- cell voltage deviations
- temperature exhaust gas
- temperature in FC stack
- electric current
- process air flow
- process air pressure
- cooling medium flow, level, pressure, temperature
- fuel flow
- fuel temperature
- fuel pressure
- gas detection in exhaust gas
- process water system level, pressure, purity
- parameters necessary to monitor lifetime/ deterioration.

The final list should be determined by the FC supplier.

8.9.7 Batteries control and monitoring system

The battery system shall have an integrated battery management system (BMS). The following parameters shall be measured:

- cell voltage
- cell or module temperature

- battery string current.

The BMS shall protect the battery system from the following faults by disconnection of the control switchgear:

- over-current
- over-voltage and under-voltage
- over-temperature.

The abnormal conditions to be alarmed shall as a minimum include:

- high cell or module temperature
- over- and undervoltage
- battery system disconnection
- tripping of battery breakers/contactor
- communication alarm
- cooling failure
- liquid cooling leakage
- low insulation level
- other safety protection functions

The final list will be determined by the batteries supplier.

8.10 Cost estimation CAPEX and OPEX

8.10.1 CAPEX

The Capital Expenditure CAPEX estimate proposed in this section constitutes a comprehensive calculation for the innovative hydrogen-electric ferry intended for the Regional route service.

Given the pioneering nature of the project and the limited availability of analogous case studies, it is recommended to adopt a contingencies-based approach, since the premium over conventional propulsion is indicative of the emerging technology status of marine fuel cells and hydrogen infrastructure. The proposed CAPEX calculation takes into account also an appropriate accuracy range, based on the project level of definition as suggested by AACE (ref. AACE International Recommended Practice No. 18R-97). The maturity level of the design achieved and the novelty of the technological choices proposed suggest a Class IV accuracy rating, as illustrated in the figures below.

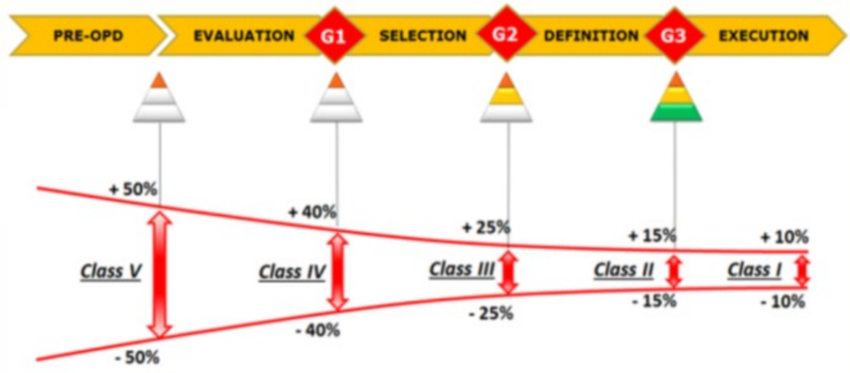


Figure 8-12: Project Development diagram

	Primary Characteristic	*Secondary Characteristic*		
ESTIMATE CLASS	**MATURITY LEVEL OF PROJECT DEFINITION DELIVERABLES** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]
Class 5	0% to 2%	Concept screening	Capacity factored, parametric models, judgment, or analogy	L: -20% to -50% H: +30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: -15% to -30% H: +20% to +50%
Class 3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	L: -10% to -20% H: +10% to +30%
Class 2	30% to 75%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: -5% to -15% H: +5% to +20%
Class 1	65% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: -3% to -10% H: +3% to +15%

Notes: [a] The state of process technology, availability of applicable reference cost data, and many other risks affect the range markedly. The +/- value represents typical percentage variation of actual costs from the cost estimate after application of contingency (typically at a 50% level of confidence) for given scope.

Table 8-13: Level of definition as suggested by AACE classification

The following main assumption has been made:

- Pricing for fuel cells 3000 Euro/kW, with prices expected to decrease in the coming years
- Current Li-ion battery costs 800 Euro/kWh, with prices expected to decrease in the coming years
- First-of-type ship with no series discount
- Hull construction cost at approx. 6 Euro/kg

In the light of the above the CAPEX has been estimated in:

- 26M Euro for the Croatian Regional Route Split
- 21M Euro for the Italian Regional Route Tronchetto-Lido.

Finally, it is important to note that potential future funding sources could be considered under the EU's Connecting Europe Facility, the state maritime fund for green shipping, the regional development funds and green shipping loans with favourable rates.

The CAPEX calculation is presented in the following Table 8-14 for the Croatian Regional Route Split-Supetar and Table 8-15 for the Italian Regional Route Tronchetto-Lido.

Description		Croatian Regional Route	
		Weight	Material cost
		[t]	[Euro]
1 - Steel structure		1 113.2	2 266 000
2 - Hull completion		71.0	699 000
3 - Hull equipment		79.8	1 791 000
5 - HVAC and insulation		19.5	482 000
6 - Electric equipment		15.9	1 734 000
7 - Accommodation and passenger spaces		58.5	1 909 000
8 - Piping		22.7	316 000
9 - ER equipment		8.1	113 000
10 - Propulsion system	2 x 500 kW	18.6	728 000
11 - Fuel cells system	1200 kW	9.5	3 600 000
12 - Li-ion battery system	700 kWh	8.7	560 000
13 - Compressed hydrogen storage system	621 kgH2	16.6	997 000
Material total cost		1 442.0	15 195 000
Labour total cost			4 559 000
Total			19 754 000
Classification & Certification			790 000
Engineering & Design			1 580 000
Shipyard Costs & Project Management			1 190 000
Commissioning			990 000
Shipyard Profit			1 190 000
Contingency			990 000
TOTAL SHIP CAPEX			26 484 000

Table 8-14: CAPEX Summary table for the Croatian Regional Route

Description		Italian Regional Route	
		Weight	Material cost
		[t]	[Euro]
1 - Steel structure		1 113.2	2 266 000
2 - Hull completion		71.0	699 000
3 - Hull equipment		79.8	1 791 000
5 - HVAC and insulation		19.5	482 000
6 - Electric equipment		15.9	1 734 000
7 - Accommodation and passenger spaces		58.5	1 909 000
8 - Piping		22.7	316 000
9 - ER equipment		8.1	113 000
10 - Propulsion system	2 x 175 kW	8.9	520 000
11 - Fuel cells system	360 kW	2.8	1 080 000
12 - Li-ion battery system	350 kWh	4.3	280 000
13 - Compressed hydrogen storage system	237 kgH2	6.8	410 000
Material total cost		1 411.5	11 600 000

Labour total cost		4 422 000
Total		16 022 000

Classification & Certification		640 000
Engineering & Design		1 280 000
Shipyard Costs & Project Management		960 000
Commissioning		800 000
Shipyard Profit		960 000
Contingency		800 000
TOTAL SHIP CAPEX		21 462 000

Table 8-15: CAPEX Summary table for the Italian Regional Route

This above CAPEXs represent a technically detailed estimate for a pioneering hydrogen-electric double-end ferry for Regional service. The cost reflects the mature technologies (as hull, propulsion, navigation) and the emerging technologies (as the fuel cells and the hydrogen systems). The premium over conventional propulsion is justified by zero local emissions, future-proof technology, potential operational savings (fuel, maintenance), regulatory compliance with emerging EU standards, potential subsidy capture. It is anyway recommended to proceed with detailed engineering phase to refine critical system specifications and confirm supplier pricing for long-lead items (fuel cells, hydrogen cylinders, azimuth thrusters)

The Fuel Cell System represents the most significant equipment cost at Euro 3.6 million and is a prime example of cutting-edge marine technology. The cost of hydrogen storage is also high due to the use of marine-certified composite cylinders and the stringent safety requirements that must be met.

The classification costs are elevated due to the innovative nature of hydrogen propulsion. This is because the classification societies, as a general rule, have limited precedent in this area.

The regional-local factors must also be taken into account: depending on the shipyard selected, construction cost may vary by ±30%.

The battery system does not have significant cost nor a large storage capacity (700 kWh), as it has been designed and sized mainly for the provision of emergency power, in accordance with the requirements of the "safe return" protocol.
The CAPEX in this section differs slightly from the initial assessment completed in Ref. [16] D.2.1.4: the present report's findings are based on a more thorough examination of the present costs for various items of the lightship.

For details about shore-based refuelling station CAPEX see Ref.[19] and [20].

8.10.2 OPEX

The OPEX (Operating Expenditure) calculation outlined in this section provides a comprehensive representation of the current annual operating costs required to manage the innovative hydrogen-electric ferry intended for the Regional route service, including but not limited to salaries, fuel, maintenance, administration, etc. The calculation concerns the annual operations of a single ship.

As mentioned in the previous section, the proposed OPEX calculation takes into account an appropriate accuracy range, based on the project level of definition as suggested by AACE.

The following main assumption has been made:

- It has been estimated that the cost of refuelling with H2 will be €10 per kilogram, plus the fixed costs for the shore-based station. It is anticipated that prices will decrease in the coming years.
- The cost of extraordinary maintenance of the fuel cell stack is estimated to be 40% of the FC CAPEX, to be amortized over seven years.
- The cost due to the battery degradation is estimated to be amortized over seven years.
- The personnel costs are based on a requirement for six members per shift, across two shifts.
- The ship service days in the years are 300.

In the light of the above the OPEX has been estimated in:

- 6.8M Euro (ship only) for the Croatian Regional Route Split
- 4.2M Euro (ship only) for the Italian Regional Route Tronchetto-Lido.

The OPEX calculation is presented in the following Table 8-16 Table 8-14 for the Croatian Regional Route Split-Supetar and Table 8-17 for the Italian Regional Route Tronchetto-Lido.

CROATIAN Regional Route SPLIT-SUPETAR		OPEX
OPEX calculation (Annual)		[Euro]
No. of working days in the year: 300		
No. of ship in the fleet: 1		
1	Fuel oil consumption	0
2	Hydrogen consumption & refueling fixed costs	3 950 000
3	Electricity consumption (from shore connection)	40 000
4	Crew, 6 people, two shifts	780 000
5	General maintenence & repairs	290 000
6	Drydocking allowance	200 000
7	Insurance	490 000
8	Administrative	210 000
9	Port fees	170 000
10	Classification Society & Flag State	60 000
11	Provisions & Stores	100 000
12	Environmental ETS	0
13	Miscellaneous	150 000
14	FC stack major overhul	210 000
15	FC standard maintenence	50 000
16	Battery degradation	80 000
17	Battery standard maitenance	20 000
OPEX total		6 800 000

Table 8-16: OPEX Summary table for the Croatian Regional Route

ITALIAN Regional Route TRONCHETTO-LIDO		OPEX
OPEX calculation (Annual)		[Euro]
No. of working days in the year: 300		
No. of ship in the fleet: 1		
1	Fuel oil consumption	0
2	Hydrogen consumption & refueling fixed costs	1 690 000
3	Electricity consumption (from shore connection)	40 000
4	Crew, 6 people, two shifts	780 000
5	General maintenence & repairs	190 000
6	Drydocking allowance	200 000
7	Insurance	430 000
8	Administrative	210 000
9	Port fees	170 000
10	Classification Society & Flag State	60 000
11	Provisions & Stores	100 000
12	Environmental ETS	0
13	Miscellaneous	150 000
14	FC stack major overhul	60 000
15	FC standard maintenence	50 000
16	Battery degradation	40 000
17	Battery standard maitenance	20 000
OPEX total		4 190 000

Table 8-17: OPEX Summary table for the Italian Regional Route

Despite the relatively high OPEX calculated value compared to a traditional diesel driven ferry, the following pros have to be considered:

- Zero emissions (regulatory compliance)
- Future-proof technology
- H2 prices expected to decline 40-50% by 2030
- Potential subsidies/incentives for green ships
- Enhanced corporate image & passenger appeal

The annual OPEX reflects the operating costs of a cutting-edge, zero-emission, hydrogen-electric double-end ferry for Regional service which are higher than those of conventional diesel alternatives. This premium is primarily driven by the cost of hydrogen fuel. However, as green hydrogen production scales up and costs decline in the coming years, the operational cost gap will narrow significantly, potentially reaching parity with diesel while maintaining zero emissions. Investing in this technology will establish the operator as a leader in sustainable maritime, offering long-term economic and environmental benefits.

This analysis is based on market conditions and technology in 2025. Actual costs may vary based on supplier negotiations, regulatory changes and operational experience.

Crew costs dominate OPEX and are strongly dependent on national wage levels, union agreements and whether the operation is public or private. For the double-end ferry with 480 passengers in EU waters, crew might include master, chief engineer, two deckhands/AB, purser and steward. The manning level will comply with flag-state safe manning.

It is important to note that capital expenditure depreciation has not been included in operating expenses because it is a long-term investment that is capitalised and depreciated in the income statement over time, in contrast to operating expenses.

The potential future government subsidies PSO (EU/Italian grants for zero-emission ships) have not been included in the OPEX calculation.

It is pertinent to acknowledge the role of the PSO (public service obligation) in this context. The PSO is a financial contribution made by a government to support essential public transport or public utility services that are often unprofitable. These services may encompass renewable energy initiatives that are not typically offered by the market. The fundamental purpose of the subsidy is to guarantee that social benefits, including connectivity and green energy, are accessible to the general public. This state aid, which is a common occurrence within the European Union, guarantees the provision of essential services. The overarching objective of these regulations is twofold: firstly, to prevent market distortions, and secondly, to achieve a balance between public needs and commercial viability through subsidies to operators.
The OPEX in this section differs slightly from the initial assessment completed in Ref. [16] D.2.1.4: the present report's findings are based on a more thorough examination of the present costs for various items included in OPEX.

For details about shore-based refuelling station OPEX see Ref.[19] and [20].

8.11 3D model

The ship shape has been modelled in 3D. Below are shown pictures of the model.

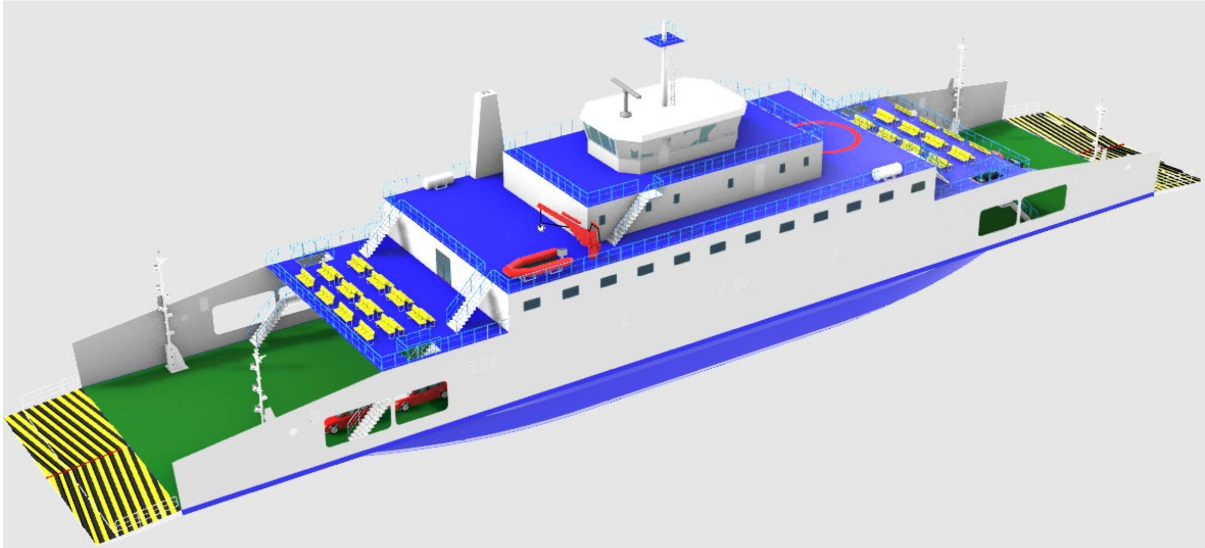


Figure 8-13: Regional 3D model (1)

Figure 8-14: Regional 3D model (2)

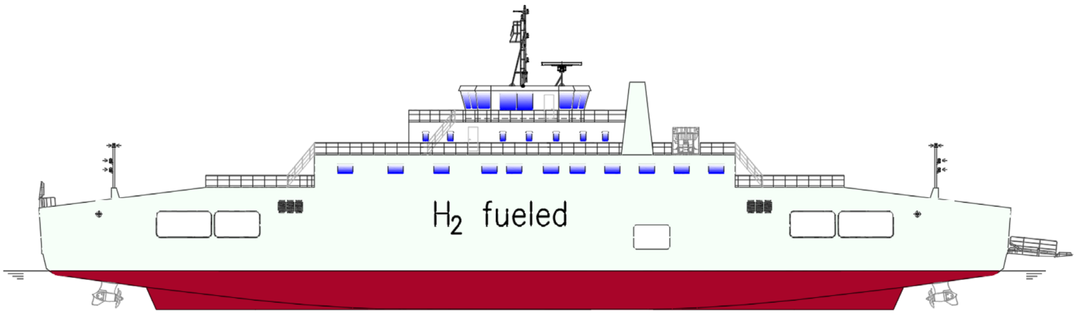
Figure 8-15: Regional 3D model with details of the hydrogen storage tanks in the hull

8.12 Power Point presentation

INTERREG_TransH2_Regional.pdf

8.13 Leaflet

REGIONAL ROUTE RO-RO PAX



SHIP MAIN CHARACTERISTICS	
Ship Type	Ro-Ro Passenger Ferry; specific coastal service
Max cars	83
Max POB	480
Length Over All	80.4 m
Length Water Line	78.6 m
Breadth (mld)	17.0 m
Depth	5.00 m
Design Draught	3.00 m
Service Speed	11.0 kn
Displacement @3.0m	abt. 2000 t

PROPULSION SYSTEM	
Power generation	PEM FC 1200 kW & Li-Ion Battery 700 kWh
Propulsion	2 x Schottel Azimuth Thruster 210 LFP
H2 Storage	n. 7 Type III pressure vessels 3740 litres each
Endurance	abt. 60 nm @11 kn

Figure 8-16: Regional Route Ship leaflet

9 Passenger ship concept design for cross-border routes

As outlined in the project documentation previously issued Ref. [16] D.2.1.4, the following cross-border route is currently under consideration:

- The route is cross-border, connecting Ancona and Split.
- The route extends for a distance of 130 nautical miles.

Following a detailed analysis of the above premises, it has been determined that the zero-emission propulsion system can be implemented for the port stay only, not for the sailing condition. The following factors provide the rationale behind this:

- The installed power for the FC should be approximately 3.5 MW. This is a prerequisite for achieving a minimum recommended sailing service speed (approx 15 knots).
- The nominal capacity of the Li-ion battery should be approximately 20 MWh, primarily due to the requirement for safe return at a minimum recommended speed (approx 12 knots).
- It is estimated that the H2 on-board storage capacity should be approximately 6,000 kilograms for one return trip (Ancona to Split and back).
- The shore-based H2 refuelling station should have a capacity of approximately 600 kg/hour, in order to meet the necessary requirements for one return trip endurance.

It is evident that the four requirements mentioned above cannot be met using currently available technology. Consequently, the ship's zero-emission energy production will be guaranteed during port stops, where more reasonable technical standards have been established, as outlined in the following pages.

9.1 General arrangement plan

General arrangement has been developed adding the hydrogen power generation system to the conventional power generation system made by diesel generators and diesel propulsion engines.

The hydrogen storage system is composed by 14 Type III cylinders. Hydrogen is stored in gaseous form at 350 barg. The hydrogen storage is arranged in open deck area.

PEM fuel cells are arranged in one dedicated space. The battery system is installed in a dedicated space.

Switchboards and power management system for the control of fuel cells and battery system are located in Control Room.

The General arrangement plan is shown below.

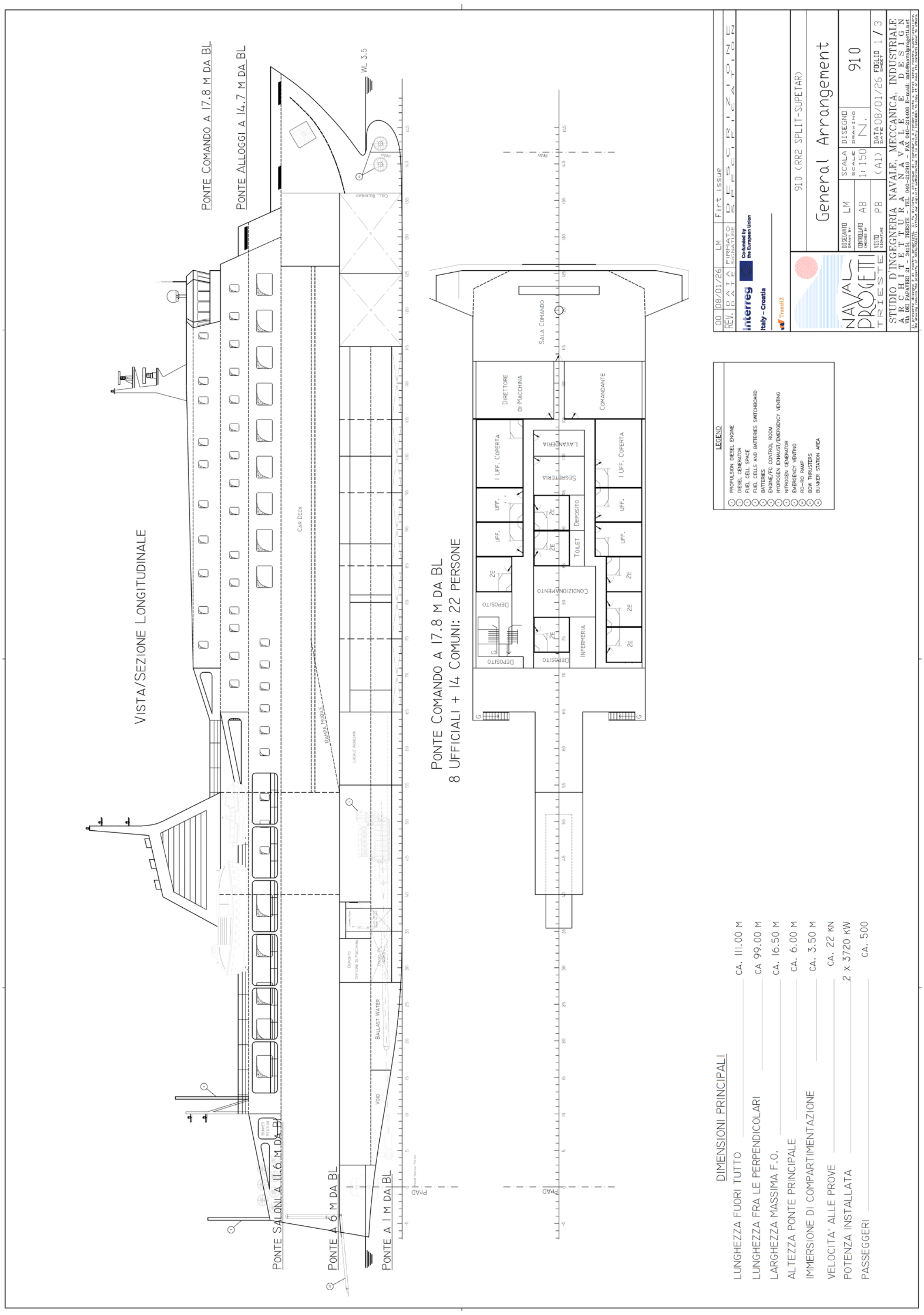


Figure 9-1: Cross-border Route ship – General Arrangement (1)

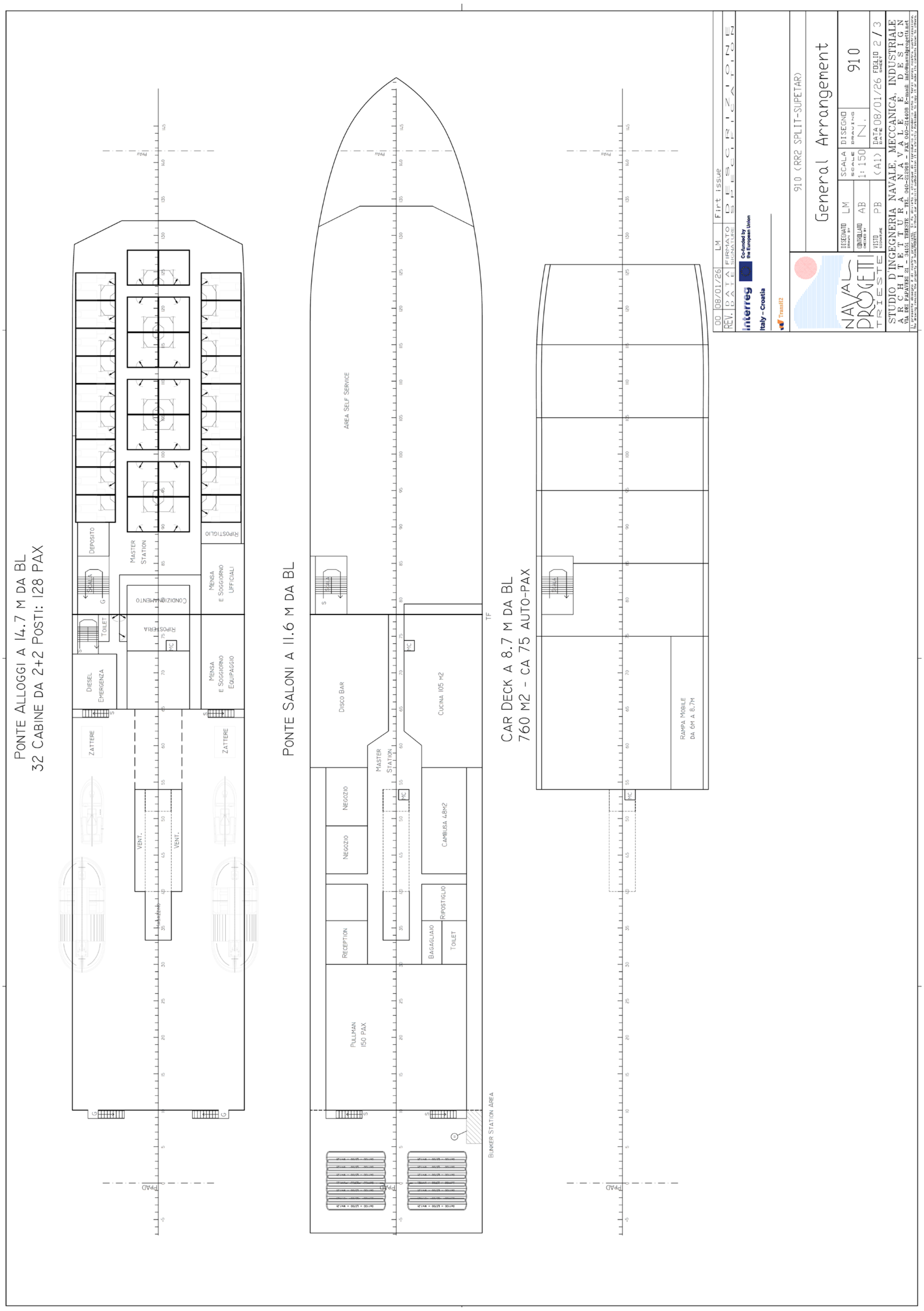


Figure 9-2: Cross-border Route ship – General Arrangement (2)

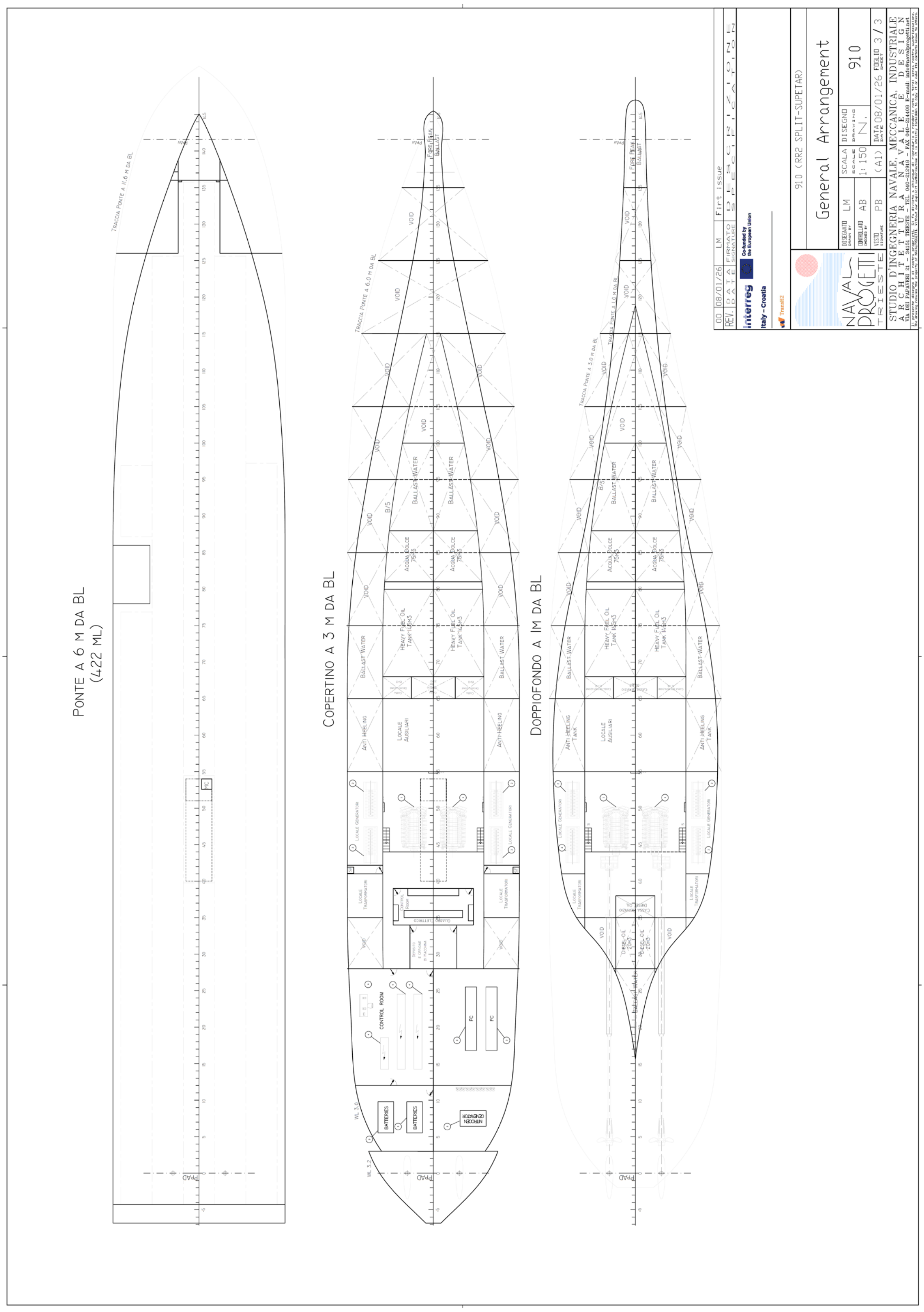


Figure 9-3: Cross-border Route ship – General Arrangement (3)

9.2 Outline specification

9.2.1 General

9.2.2 Introduction

This outline specification describes the ship main characteristics as well as the main propulsion system.

The ship is propelled by a diesel conventional propulsion system and the electric power generation is provided by 4 diesel generators. The diesel fuelled systems will be used during navigation and manoeuvring operations.

The power generation during the port stay is provided by PEM fuel cells, fuelled by gaseous hydrogen, and battery storage system.

The gaseous hydrogen is stored in cylinders with a pressure of 350 barg.

9.2.3 Operating area

The ship will operate in cross-border routes.

The route considered for this analysis is Split-Ancona.

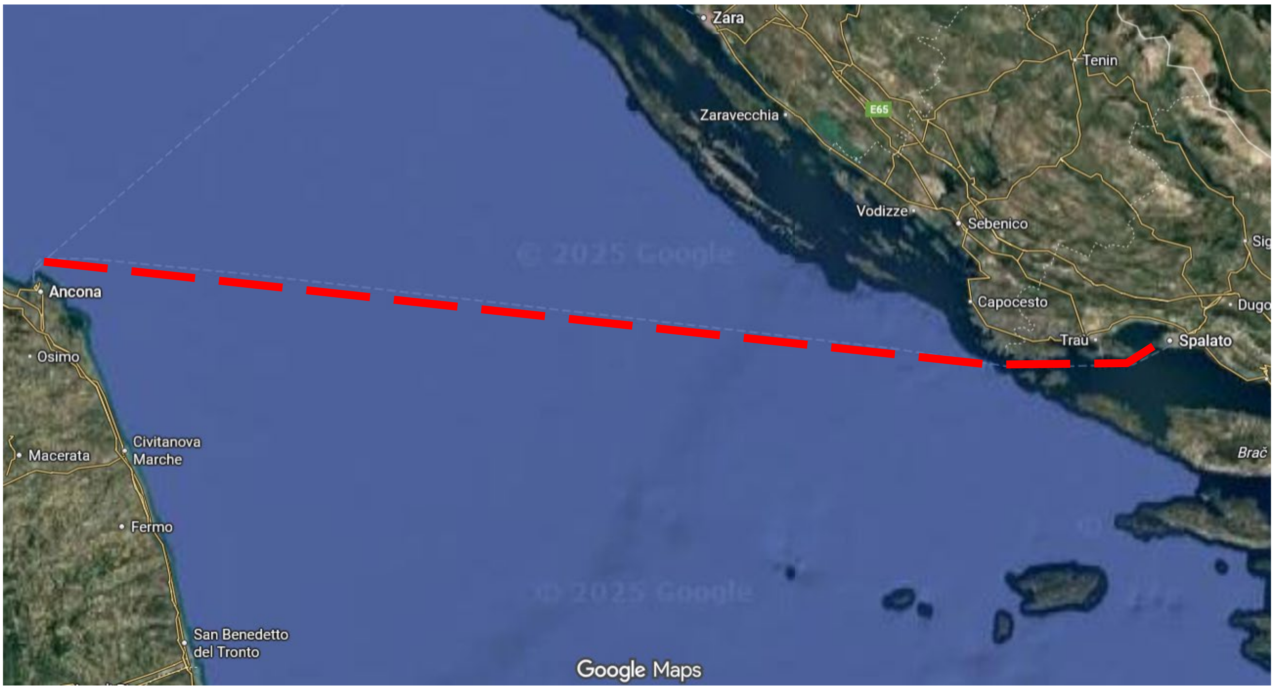


Figure 9-4: Cross-border Route

9.2.4 Ship description

The ship will be designed and built as a RO-RO PAX motor ship for transporting trailers, cars, and approximately 460 passengers.

The ship will have twin propellers with two diesel engines located at the stern of the ship, with a cargo hold located forward under the main deck, a main deck hold, and an upper deck hold.

The ship will have a continuous double bottom with fuel tanks designed to obtain CLEAN SEA certification, watertight bulkheads, a bulbous bow, a transom stern, and longitudinal compartmentation at B/5.

Two bow thrusters will be installed.

Access to the cargo area will be from land via a stern door/ramp directly to the main deck.

In the forward area of the main deck garage, there will be a upper car deck consisting of hydraulically operated panels and served by a mobile ramp.

The accommodation area will be located on the decks above the Accommodation Deck, including the Accommodation Deck itself.

Passengers will reach this area via a fixed staircase.

The side casings will be empty spaces and connected on the starboard and port sides.

When necessary, the ballast water will be carried in the dedicated double bottom tanks.

An anti-heeling system will be provided.

9.2.5 Ship main characteristics

Ship main characteristics are reported below:

Overall length abt.	110.00 m
Length between perpendiculars	99.00 m
Beam abt.	16.50 m
Height at deck level abt.	6.00 m
Height at main deck abt.	11.60 m
Full load draft abt.	3.50 m
Corresponding deadweight tonnage abt.	1 200 t

Maximum continuous engine power	2 x 3,720 kW
Speed at full load tests with 85% MCR	21.8 kn
Service speed 85% MCR and 15% Sea Margin	21.0 kn

9.2.6 Speed and power

The ship in full load trials in deep water, with a clean hull and calm sea and wind conditions, will have a speed of 21.8 knots at 85% MCR.

Sea trials will be carried out at maximum possible draft, loading all available ballast water.

The report on contractual conditions will be based on tank trials carried out at the same displacements.

Before sea trials, the ship will be placed in dry dock for hull cleaning.

9.2.7 Power plant

9.2.7.1 Zero-emission power plant

The ship shall be equipped by a zero-emission power plant to power auxiliary services during port stay. The system will be composed by hydrogen powered PEM fuel cell and a battery storage.

The hydrogen will be stored in gaseous form in compressed cylinders filled through a dedicated bunker station.

The ship energy management system will control fuel cell, batteries, propulsions system and will optimize ship energy consumption and fuel cell and battery usage.

9.2.7.2 Conventional power plant

The engine will be located amidships.

There will be two medium-speed main engines, each operating on the diesel cycle, four-stroke, with direct fuel injection, supercharged by turbochargers, and with supercharged air cooling.

The engines will be Wartsila 12V26A type, 12-cylinder V-type, with a maximum continuous rating (MCR) of 3,720 kW at 900 rpm. Total installed power: 7,440 kW

Each engine is coupled to a shaft line via a 1-input, 1-output gear reduction unit with built-in thrust bearing, complete with service and reserve oil pumps, coolant and oil filter, as well as accessories and pipes for lubricating the reduction unit, incorporated into the same.

Each engine is connected to the gearbox via a flexible coupling and a disc clutch.

The propeller pitch control mechanism will be located on the forward side of the gearbox, coaxially with the shaft line.

A complete system consisting of boilers, auxiliary machinery, and steam accessories for heating the fuel tanks and various on-board services will be supplied.

The system will include:

- 1 oil-fired boiler with a capacity of approximately 800 kg/h of saturated steam at 7 bar.

There are two shaft lines, made of forged steel.

Two 4-blade adjustable propellers will be installed, with blades and hubs made of NI-AL-BRONZE.

Four 600 kW, 1800g/1 diesel alternator sets will be provided, each consisting of a 4-stroke diesel engine with non-reversible turbocharger, powered by fuel oil.

An emergency diesel generator set will be supplied, consisting of a diesel engine and an approx. 50 kW alternator.

The refrigeration system will be centralized with a fresh water and sea water circuit, high and low temperature.

The automation and remote control system will be designed so that the propulsion system and, in general, the entire engine room can operate with the engine room unattended 24 hours a day and so that it can receive the notifications provided for in Chapter 1.

In principle, the following criteria will be followed:

- centralized command and control of the propulsion system, electrical system, navigation, garage control, and ballast system will be provided;

- the engine rooms, including the SCP, will be permanently unattended during the operational phases from “stand-by” to “finished in the engine room,” i.e., during navigation and maneuvering;

No fewer than four stations will be provided, located as required for functional purposes, two of which will be in the ECR.

The stations will be equipped with 19" color graphic displays.

9.2.8 Battery storage

A power pack with lithium batteries shall be provided for fuel cells peak shaving and fuel cell buffer.

The battery storage shall be arranged in a dedicated room as per General arrangement.

The total battery power installed shall be 350 kWh.

The battery pack shall be of sealed type and water cooled.

Fire detection system and suitable fire extinguishing system shall be installed in battery room.

The BMS shall be connected to ship PMS for energy management.

9.2.9 Hydrogen storage

Hydrogen in gaseous form shall be stored on board to feed fuel cell systems.

A total of fourteen (14) gas cylinders shall be arranged in open area above main deck.

The gas cylinders shall be of Type III.

The gaseous hydrogen shall be stored at a pressure of 350 barg.

The storage system shall be provided of suitable relief valves for emergency gas release. Hydrogen venting shall lead to venting mast.

The storage area shall be provided of suitable fire and gas alarm.

9.2.10 Fuel cell system

The ship will be provided by PEM fuel cell for power generation in harbour condition. The total installed capacity shall be 1200 kW. Fuel cells modules shall be arranged in a dedicated room.

Here below are reported the characteristics of one fuel cell module only for reference (e.g. Ballard).

Product Specifications

Performance	
Rated power	200kW
Minimum power	55kW
Peak fuel efficiency	53.5%
Operating voltage	350 – 720 V DC
Rated current [1]	2 x 300 A or 1 x 550 A
System cooling output	Max 65° C
Stack technology	
Heat management	Liquid cooled
H_2 Pressure	3.5 – 6.5 barg
Physical	
Dimensions (l x w x h) [2]	1209 mm x 741 mmx 2195 mm
Weight (estimate) [3]	1000 kg
Environmental protection	IP44
Engine room (DNV CG-0339)	+0°C – +45°C
Minimum start-up temperature	0°C
Short-term storage temperature	-40°C – +60°C
Reactants and Coolant	
Type	Gaseous hydrogen
Composition	As per SAE spec. J2719 and ISO 14687:2019 Type I, Type II – Grade D
Oxidant	Air
Composition	Particulate, Chemical and Salt filtered
Coolant [4]	Water or 50/50 glycol
Safety Compliance	
Certifications	DNV-Type Approval , Lloyds Register Approval and ABS (American Bureau of Shipping) Approval
Enclosure	Sealed secondary barrier for hydrogen
Monitoring	
Control interface	Ethernet, CAN
Emissions	
Exhaust	Zero-emission

Table 9-1: Typical fuel cell characteristics

The fuel cell modules shall be liquid cooled. Suitable cooling, venting, drain and inerting systems shall be provided to fuel cells modules. Adequate redundancy of auxiliary systems shall be provided in case of system one single failure.

The fuel cell system shall be controlled by ship PMS.

9.2.11 Bunker station

Ship shall be provided of one bunker station at starboard, as represented in the General arrangement.

In addition to the conventional connections, the bunker station shall have two connection for gaseous hydrogen filling and one cable connection for ESD system.

Bunker gas manifold shall be isolated by two valves as required by IGF code. Pressure relief valve shall be provided to bunker gas manifold leading to vent mast.

The gas pipe coupling shall be of quick release type.

The bunker station shall have gas and fire alarm.

A fire extinguishing system shall be provided in bunker station area.

9.2.12 Hydrogen auxiliary systems

The systems described in this chapter are connected to hydrogen power system functionality and are additional to ship conventional systems for fuel oil.

9.2.12.1 Inerting system

The inerting is done to minimise the level of oxygen in a given space and prevent oxygen and/or moisture from coming into contact with reactive or adsorptive products.

The main aim of the inerting are to:

- Prevent explosive atmospheres from forming;
- Ensure safe startup and shutdown of plants and apparatus;
- Avoid explosion risks during storage and transport of combustible substances;
- Protect products against atmospheric oxygen when oxidation reactions would impair quality;

- Protect against atmospheric moisture, either to maintain product quality or to ensure optimal downstream processing;
- Prevent health and safety hazards during maintenance of plants, apparatus and pipelines;

Purging process introduces an inert gas in the pipeline in order to displace a gas from it.

The inert gas systems shall include the nitrogen inert system for inertization of gaseous hydrogen system.

Nitrogen system shall be provided for the purging/inertization of the piping system.

Purging of piping system shall be performed with displacement method. The inert gas system shall have the capability to purge hydrogen from gaseous piping system lowering the hydrogen concentration below 4%.

Nitrogen shall be produced by a nitrogen generator and stored in compressed cylinders of 50 l each at abt. 300 bar with purity of 99.99% in a dedicated storage room.

Each hydrogen pipe section between two segregation valves shall be provided with connection to inerting system.

9.2.12.2 Venting system

The venting system shall be designed in order to safely vent hydrogen from hydrogen storage tanks and hydrogen piping to vent mast in case of system overpressure.

Each hydrogen pipe section between two segregation valves shall be provided with relief valve system connected to venting system.

Venting pipe shall be of single walled type and the material shall be in stainless steel suitable for hydrogen. Connections between pipes shall be welded.

9.2.12.3 Ventilation system

The ventilation system for the spaces dedicated to handling of hydrogen onboard, including PEMFC area, shall be designed to dilute and evacuate possible hydrogen losses in served spaces. Ventilation system shall also provide: the necessary process air to the PEMFC, extraction of FC exhaust gases and the sub-modules ventilation air. An effective extraction system shall be designed in order to grant requested air changes per hour for each served area. Both for extraction and supply system, attention must be paid to properly segregate ducting from different hazardous spaces.

Supply fans shall be designed in order to grant 30 air changes/hour, both to the served hazardous spaces and non-hazardous spaces.

All supply circuits shall be ducted and served by dedicated fans. Air distribution shall be provided both at the highest levels of the room and at ground-level. Air shall be locally distributed with the DIRIVENT System or other equivalent, which provides efficient air mixing and destratification.

Ventilation system shall provide also the necessary process and ventilation air to FC sub-modules. The air quantity, as well as air characteristics (temperature, filtration grade), shall be taken in accordance with FC supplier.

9.2.12.4 Extraction/exhaust system

The extraction system for non-hazardous areas (FC Room) shall be designed in such a way as to ensure separation between hazardous ducts and non-hazardous extraction.

The extraction systems for hazardous spaces shall consists of dedicated ducts with dedicated fans for the purpose of segregate each hazardous spaces from each other and from not-hazardous spaces. Air balance will be such to obtain under-pressure, in order not to allow the spreading of possible leakages.

The sub-modules ventilation air exhaust system shall consist of a dedicated duct for each pair of sub-modules (in accordance with FC supplier).

The FC exhaust gas extraction system shall consist of a dedicated duct with a dedicated (axial) extractor that convey gases directly into the funnel.

The FC exhaust gas extraction system shall consist of a dedicated duct with a dedicated (axial) extractor that convey gases directly into the funnel.

9.3 Stability evaluation

This document aims to verify the stability of the TransH2 project ship in her intact condition for the Cross-border Route. The stability of the ship has been verified in accordance with the IMO criteria for passenger ships as per the 2008 IS Code, by performing an analysis for different load conditions. All the stability requirements have been investigated and found to be in compliance with the referenced rules, as detailed in the following sections.

9.3.1 Stability analysis

The stability analysis was carried out using GHS software by Creative Systems Inc. Port Townsend, Wasington, USA, Licence No. NPI NavalProgetti20.4898DE306FAE. The hydrostatic model comprises displacement elements (green), sail elements (red), tank elements (dark green), and critical points (weathertight and flooding points). The following three-dimensional representation illustrates the hydrostatic model that was utilised.

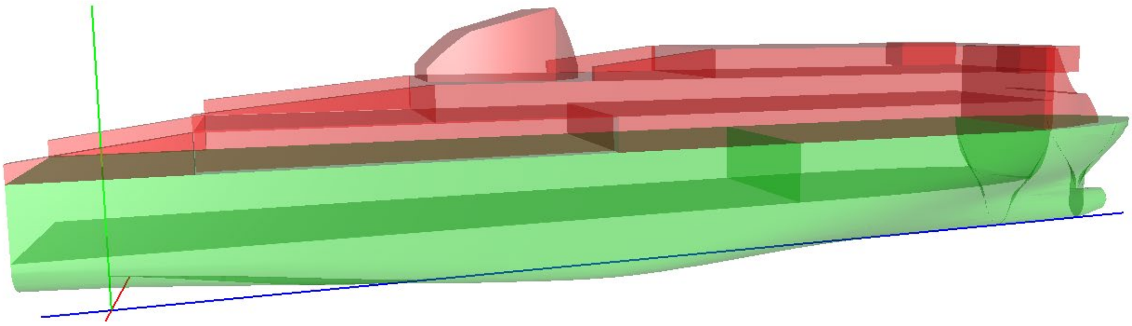


Figure 9-5: Cross-border Route ship hydrostatic model

9.3.2 Loading Conditions

Stability verification was performed for the most characteristic load conditions. In this case, the following load conditions were examined:

Load Condition n. 1: Full Load Departure
Load Condition n. 2: Full Load Arrival
Load Condition n. 3: Ballast Departure
Load Condition n. 4: Ballast Arrival

Loading Conditions	Weight	LCG	TCG	VCG
		@ Aft PP	@ C.L.	@ B.L
	t	m	m	m
Load Condition n. 1: Full Load Departure	3 235	45.42	0.00	7.57
Load Condition n. 2: Full Load Arrival	3 235	45.41	0.00	7.39
Load Condition n. 3: Ballast Departure	2 564	46.77	0.00	6.73
Load Condition n. 4: Ballast Arrival	2 564	46.75	0.00	6.51

Table 9-2: Loading Conditions Summary

The loading condition breakdown is offered in the following tables:

Load Condition n. 1: Full Load Departure	Q.ty	Sp.Wt.	Weight	LCG	TCG	VCG	FSM
			[t]	[m]	[m]	[m]	[t x m]
Lightship			2 008	43.77	0.00	7.74	0
Cargo: Trailers	400	1.625	650	40.60	0.00	7.80	0
Cargo: Cars	75	1.500	113	63.00	0.00	19.60	0
Compressed hydrogen H2 @ 350 bar	71	0.024	1.69	0.23	0.00	12.73	0
Fuel Oil: Departure			79	46.90	0.00	3.00	44
Fresh Water: Departure			159	51.10	0.00	3.00	77
Soundry Tanks			30	35.00	0.00	3.00	1
Ballast Water			135	66.90	0.00	0.40	100
Passengers, Crew, Prow. etc.			60	60.90	0.00	13.46	0
Displacement			3 235	45.42	0.00	7.57	223

Table 9-3: LC1 breakdown

Load Condition n. 2: Full Load Arrival	Q.ty	Sp.Wt.	Weight	LCG	TCG	VCG	FSM
			[t]	[m]	[m]	[m]	[t x m]
Lightship			2 008	43.77	0.00	7.74	0
Cargo: Trailers	400	1.63	650	40.60	0.00	7.80	0
Cargo: Cars	75	1.50	113	63.00	0.00	19.60	0
Compressed hydrogen H2 @ 350 bar	1.5	0.024	0.04	0.23	0.00	12.73	0
Fuel Oil: Arrival			8	46.90	0.00	1.20	44
Fresh Water: Arrival			16	51.10	0.00	1.20	77
Soundry Tanks			30	35.00	0.00	3.00	1
Ballast Water			351	56.00	0.00	0.50	100
Passengers, Crew, Prow. etc.			60	60.90	0.00	13.46	0
Displacement			3 235	45.41	0.00	7.39	223

Table 9-4: LC2 breakdown

Load Condition n. 3: Ballast Departure	Q.ty	Sp.Wt.	Weight	LCG	TCG	VCG	FSM
			[t]	[m]	[m]	[m]	[t x m]
Lightship			2 008	43.77	0.00	7.74	0
Cargo: Trailers	0	1.63	0	40.60	0.00	7.80	0
Cargo: Cars	0	1.50	0	63.00	0.00	19.60	0
Compressed hydrogen H2 @ 350 bar	71	0.024	1.69	0.23	0.00	12.73	0
Fuel Oil: Departure			79	46.90	0.00	3.00	44
Fresh Water: Departure			159	51.10	0.00	3.00	77
Soundry Tanks			30	35.00	0.00	3.00	1
Ballast Water			226	68.50	0.00	0.40	100
Passengers, Crew, Prow. etc.			60	60.90	0.00	13.46	0
Displacement			2 564	46.77	0.00	6.73	223

Table 9-5: LC3 breakdown

Load Condition n. 4: Ballast Arrival	Q.ty	Sp.Wt.	Weight	LCG	TCG	VCG	FSM
			[t]	[m]	[m]	[m]	[t x m]
Lightship			2 008	43.77	0.00	7.74	0
Cargo: Trailers	0	1.63	0	40.60	0.00	7.80	0
Cargo: Cars	0	1.50	0	63.00	0.00	19.60	0
Compressed hydrogen H2 @ 350 bar	1.5	0.024	0.04	0.23	0.00	12.73	0
Fuel Oil: Arrival			8	46.90	0.00	1.20	44
Fresh Water: Arrival			16	51.10	0.00	1.20	77
Soundry Tanks			30	35.00	0.00	3.00	1
Ballast Water			442	59.00	0.00	0.50	100
Passengers, Crew, Prow. etc.			60	60.90	0.00	13.46	0
Displacement			2 564	46.75	0.00	6.51	223

Table 9-6: LC4 breakdown

9.3.3 Lightship

The value of the lightship was calculated on the basis of a detailed load list and with the aid of the available database. The weight and center of gravity of the lightship were found to be:

Weight	: 2008 t
LCG	: 43.77 m from Aft Pp
TCG	: 0.00 m off CL
VCG	: 7.74 m above base line

Below is a summary table of the main items that make up the lightship:

Description	Weight
	[t]
1 - Steel structure	864.4
2 - Hull completion	98.0
3 - Hull equipment	333.0
4 - Hull & engine room auxiliaries	167.0
5 - HVAC and insulation	80.0
6 - Electric equipment	64.0
7 - Catering	13.0
8 - Cabins	78.0
9 - Public areas	74.0
10 - Propulsion system	178.0
11 - Fuel cells system	9.5
12 - Li-ion battery system	4.9
13 - Compressed hydrogen storage system	44.2
Lightship	2 008.0

Table 9-7: Lighship weight breakdown

9.3.4 General Stability Criteria

The ship shall comply with the IMO Intact Stability Code (IMO 2008 IS Code Part A Ch.2.2) as follows:

LIM (1) The area under the righting lever curve shall not be less than 0.055 metre-radians up to an angle of heel equal to 30°.

LIM (2) The area under the righting lever curve shall not be less than 0.09 metre-radians up to an angle of heel equal to 40° or the angle of down-flooding if this is less than 40°.

LIM (3) The area under the righting lever curve between the angles of heel of 30° and 40° or between 30° and the angle of down-flooding if this angle is less than 40°, shall not be less than 0.03 metre-radians.

LIM (4) The righting lever shall be at least 0.20m at an angle of heel equal to or greater than 30°.

LIM (5) The maximum righting lever shall occur at an angle of heel not less than 25°. If this is not practicable, alternative criteria may be applied.

LIM (6) The initial metacentric height GM0 shall not be less than 0.15m.

9.3.5 Alternative Stability Criteria

The following equivalent criteria should be applied where the ship's characteristics render compliance with IMO 2008 IS Code Part A Ch.2.2.3 impracticable, i.e. when the maximum righting lever shall occur at an angle of heel less than 25°:

LIM (1): the area under the curve of righting levers (GZ curve) should not be less than 0.07 metre-radians up to an angle of 15° when the maximum righting lever (GZ) occurs at 15° and 0.055 metre-radians up to an anglc of 30° whcn thc maximum righting lever (GZ) occurs at 30° or above. Where the maximum righting lever (GZ) occurs at angles of between 15° and 30°, the corresponding area under the righting lever curve should be: 0.055 + 0.001 (30°-AngGZmax) metre-radians;

LIM (2): the area under the righting lever curve (GZ curve) between the angles of heel of 30° and 40°, or between 30° and <pr if this angle is less than 40°, should be not less than 0.03 metre-radians;

LIM (3): the righting lever (GZ) should be at least 0.20 m at an angle of heel equal to or greater than 30°;

LIM (4): the maximum righting levcr (GZ) should occur at an angle of heel not less than 15°;

LIM (5): the initial transverse metacentric height (GM0) should not be less than 0.15 m;

9.3.6 Weather criterion (2008 IS CODE)

The ability of a ship to withstand the combined effects of beam wind and rolling should be demonstrated for each standard condition of loading, with reference to figure below, as follows:

4. The ship is subjected to a steady wind pressure acting perpendicular to the ship's centreline which results in a steady wind heeling lever (lw1);
5. From the resultant angle of equilibrium (Fi0), the ship is assumed to roll owing to wave action to an angle of roll (Fi1) to windward;
6. The ship is then subjected to a gust wind pressure which results in a gust wind heeling lever (lw2);

- LIM (27) under these circumstances, area "b" should be equal to or greater than area "a".

- LIM (28) the angle of heel under action of steady wind (Fi0) should not exceed 16° or 80% of the angle of deck edge immersion, whichever is less.

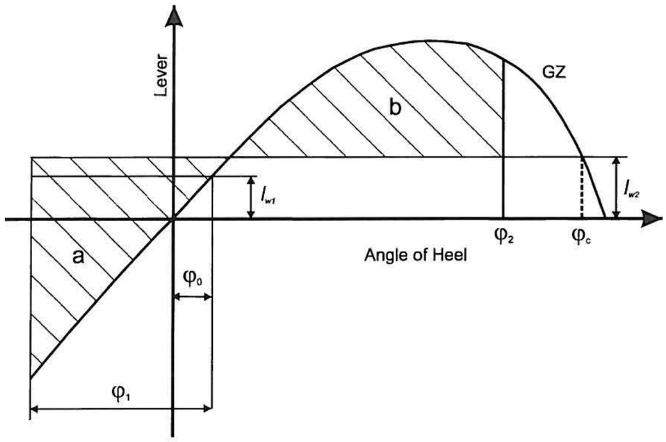


Figure 9-6: IMO Weather Criterion

The angles in figure are defined as follows:
FI0 = angle of heel under action of steady wind
FI1 = angle of roll to windward due to wave action
FI2 = angle of roll downflooding or 50° or FIc , whichever is less, where:
FIf = angle of heel at which openings in the hull, superstructures or deck-houses which cannot be closed weathertight immerse.
FIc = angle of second intercept between wind heeling lever (lw2) and GZ curve.

9.3.7 Passenger Ship Stability Criteria

As per IMO 2008 IS Code Part A Chapter 3.1, the passenger ships shall comply with the requirements listed above.

LIM (31): in addition, as per IMO 2008 IS Code Part A Chapter 3.1.1, the angle of heel on account of crowding of passengers to one side shall not exceed I 0°.
LIM (32): in addition, the angle of heel on account of turning shall not exceed 10° when calculated using the following formula:

$$M_r = 0.200 \cdot (V_s^2)/L_{wl} \cdot \Delta \cdot (KG - d/2)$$

where:

M_r = heeling moment (kNm)

V_s = service speed (m/s)

LWL = length of ship at waterline (m)

Δ = displAcement (t)

d = mean draught (m)

KG = height of centre of gravity above baseline (m)

9.3.8 Stability Analysis Results

The following tables show the results of the stability analysis, which demonstrate that all stability requirements are satisfied.

LC	Displ	Draft	Trim	Heel
		@ B.L.	@ PP	
			+Aft	+Stbd
	t	m	m	deg
LC1	3235	3.49	0.01	0.0
LC2	3235	3.49	0.02	0.0
LC3	2564	2.99	0.01	0.0
LC4	2564	2.99	0.02	0.0
Max	3 235	3.49	0.02	0.00
Min	2 564	2.99	0.01	0.00
Status				

Table 9-8: Loading Conditions results

LC	LIM (11)	LIM (12)	LIM (2)	LIM (3)	LIM (4)	LIM (5)			LIM (27)	LIM (28)	LIM (31)	LIM (32)
	Area	Area	Area	RA	Angle	GMT			Weather	Steady wind	Crowding	Turning
	0° - 30°	0° - 40°	30° - 40°	30deg	@ RA Max				A2/A1	Heel	2.89	0.67
	> 0.055	> 0.090	> 0.030	> 0.20	>25	> 0.15			>1	<16°;80%DI	<10	<10
	rad.m	rad.m	rad.m	m	deg	m			-	deg	deg	deg
LC1	0.271	0.402	0.131	0.777	28.8	2.63			1.06	5.6	2.2	3.1
LC2	0.295	0.444	0.149	0.867	30.7	2.81			1.26	5.2	2.1	2.8
LC3	0.424	0.641	0.217	1.239	60.9	3.92			1.54	4.7	1.9	1.9
LC4	0.455	0.695	0.240	1.355	61.5	4.15			1.75	4.5	1.8	1.7
Max	0.455	0.695	0.240	1.355	61.5	4.15			1.75	5.6	2.2	3.1
Min	0.271	0.402	0.131	0.777	28.8	2.63			1.06	4.5	1.8	1.7
Status	Passed	Passed	Passed	Passed	Passed	Passed			Passed	Passed	Passed	Passed

Table 9-9: Loading Conditions results

9.4 Power prediction

This section presents calculations relating to ship hydrodynamic resistance and power forecasts for the ferry analysed on the Cross-border route between Italy and Croatia. This analysis does not in any way affect the specificity of the project in question, namely the production of energy using FC when the ship is in port. However, this analysis is provided for the sake of completeness.

9.4.1 Ship main characteristics

Description	Symbol	Value	Unit
Length Overall	LOA	111.00	[m]
Length at Waterline	LWL	104.00	[m]
Max. Breadth	B	16.50	[m]
Breadth at Waterline	BWL	16.50	[m]
Depth	H	6.00	[m]
Max Draft / Power estimation draft	T	3.50	[m]
Speed	V	21.0	[kn]
Number of propellers		2	
Total Propulsion Power @100% MCR	Pmax	2 x 3 720 = 7 440	[kW]
Class Notation	✠ 100A1.1-Nav.IL Mn. Tr. (Ro-Ro) Tp NAV(Ib) AUT-UMS		

Table 9-10: Cross-border Route ship main characteristics

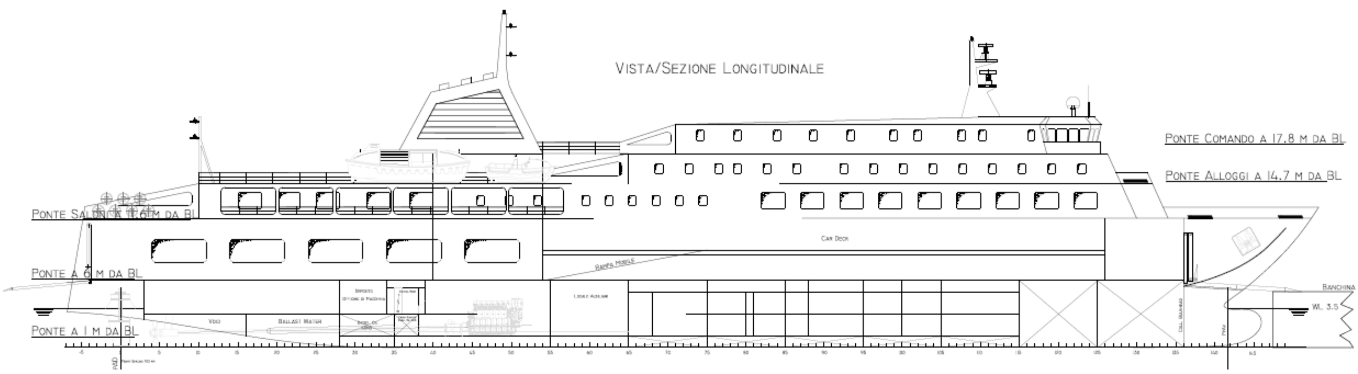


Figure 9-7: Cross-border Route ship longitudinal view

9.4.2 Description of power plant

The propulsion power plane delivers a maximum power of 7.44 MW (2 x 3720 kW), which is sufficient to ensure a speed of 21 knots in open water conditions and sea margin 15% (PB = 6345 kW), running at approximately 84% MCR.

The twin-screw configuration consists of two shaft lines with 4-blade controllable pitch propellers 2.3 m diameter driven by two diesel propulsion engine.

9.4.3 Resistance analysis

Resistance prediction was carried out using NavCad software by HydroComp Inc. New Hampshire, USA, Licence No. 18.02.0071.0156.V0691. The resistance curve for the ferry is shown in the following figure for the Cross-border Ancona – Split route:

Cross-border Route: Ancona-Split

- Wind speed: 27.0 kn
- Significant wave height: 1.0 m (*)
- Sea depth (assumed constant): 400 m

(*) Report Ref. [15] D.2.1.3 shows that significant wave heights of between 1 and 4 metres are to be expected for the Ancona Split route. However a wave with Hsig 1 m was assumed in the resistance calculations because it is more consistent with a sustainable operating limit for navigation at the expected speed.

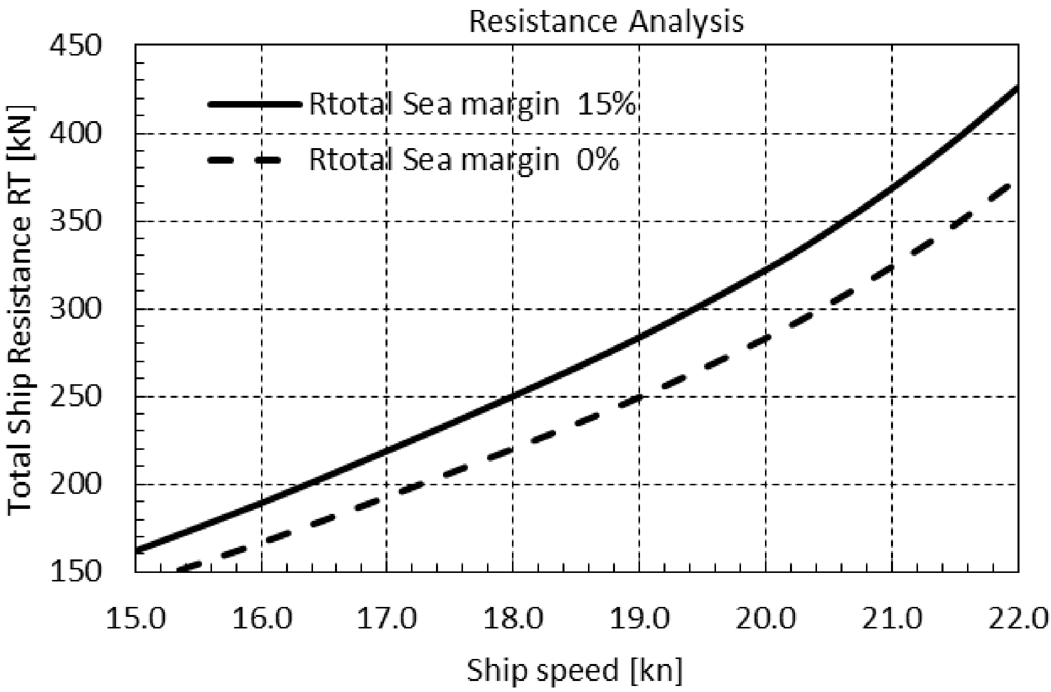


Figure 9-8: Total Ship Resistance RT [kN] – Cross-border Route

9.4.4 Power analysis

In order to obtain the final power prediction data, the basic setting of the programme is changed from resistance mode to propulsion mode. This makes it possible to obtain information relating to cavitation, as well as brake power values for the motors selected. The first result of the power prediction, shown in the following graph, is the brake power:

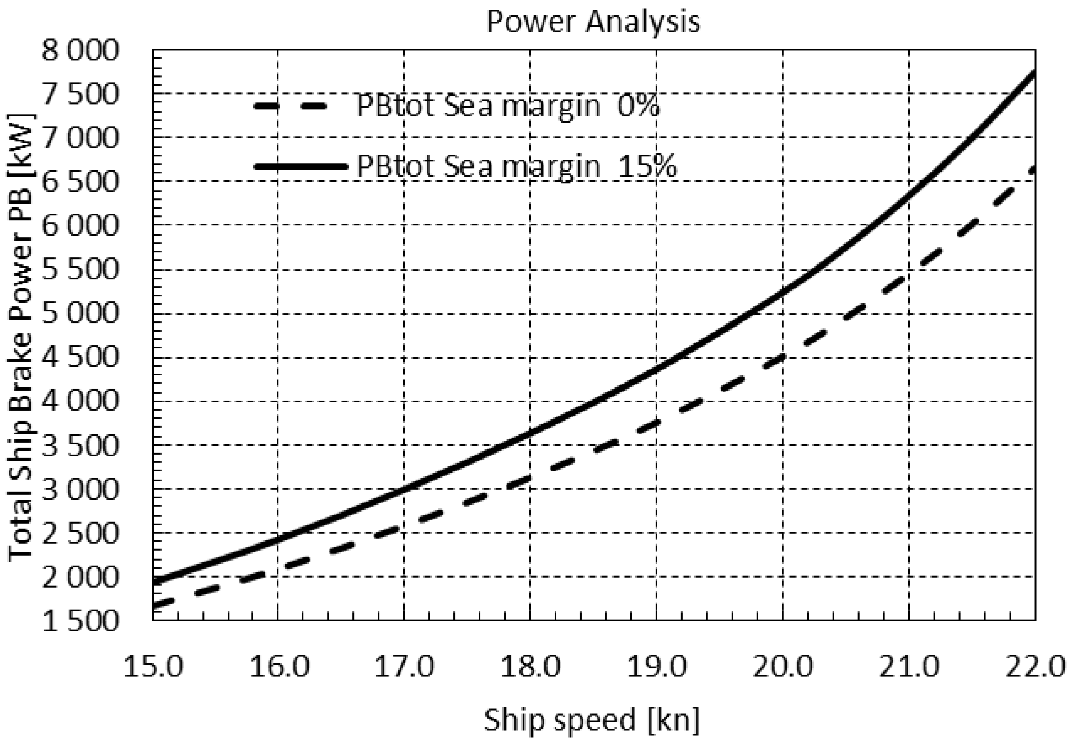


Figure 9-9: Total Ship Brake Power PB [kW] – Cross-border Route

At a speed of 21.0 knots (Ancona-Split Route), the required brake power PB is 6 345 kW, corresponding to 84% of the maximum power deliverable by the propulsion systems (84% MCR).

9.5 Bunkering

For the compressed gaseous hydrogen bunkering system see section 8.5 Bunkering.

9.6 Energy Balance

9.6.1 General

This section studies the ship's energy balance in order to assess the amount of hydrogen (H2) that will be carried on board at the start of a return trip at the port of Ancona (the starting conditions at departure). The determined amount of H2 will be stored in cylinders where the gas will be compressed to 350 bar.

Regarding the number of refuelling operations to be carried out each day, the arrangement of the cylinders, and other aspects, reference has been made to Doc. D.2.1.4 'Option analysis for the introduction of hydrogen-fuelled solutions in three use cases'.

9.6.2 H2 energy reserve

The H2 energy reserve ER has been evaluated according to the following basic assumption:

H2ER = [Pn*Tn + Pp*Tp] * n

where:

H2ER: the energy consumed in one operative day, kWh
Pn: the mean power (propulsion & auxiliaries) developed during navigation, kW
Tn: the time for one trip navigation, h
Pp: the mean power (auxiliaries) developed during port stay, kW
Tp: the time for one port stay, h
n: the number of trip in a day

The inner net volume for each cylinder has been evaluated according to the following basic assumption:

VOLcyl = H2vol / NR / NC

where:

VOLcyl: the internal volume of one cylinder
H2vol: the H2 @ 350 bar volume consumed in one operative day
NR: the number of refuelling in a day
NR: the number of cylinders

When applying the above formula, it should be noted that in our specific case (i.e. for the Cross-border route Ancona–Split where the power generation for propulsion, auxiliaries and hotelling will be provided by diesel engines during sailin) we will have:

Tn: 0 h
Pp: 1080 kW
Tp: 20 h (max in Split)
n: 1
NR: 1

In order to calculate the H2 @ 350 bar volume consumed in one operative cycle, the following aspects must also be taken into consideration, as the fuel cells (FC) efficiency 40% (conservative assumption retrieved from FC manufacturer), an overall electric efficiency 98%, heel 5 barg, H2 net heat value 33.31 kWh/kg (from National Institute of Standards and Technology – Refprop), H2 density 23.72 kg/m3 (at gaseous phase, 293 K, 350 barg), H2 density heel 0.49 kg/m3 @ 293 K, 5 barg.

The H2 energy reserve shall be stored in 350 bar composite cylinders with the following characteristics:

Cross-border Route Ancona-Split	
Mean power during sailing, kW:	N.A.
Mean power during port stay, kW:	1080
H2 consumption for one port stay, kg/:	1654
No. of refuelling for one return journey (two trips):	1
Cylinder length, m:	5.7
Cylinder outer diameter, m:	1.30
Cylinder net inner volume, litres:	5087
Number of cylinders:	14
One cylinder (empty) weight, kg:	2961
H2 weight in one (full) cylinder, kg:	121
Time for one refuelling(*), h	8.0

(*) Flow rate 207 kg/h for cylinders refuelling, plus 83 kg/h for hotelling during port stay in Ancona: total is 290 kg/h (two refuelling connections, 145 kg/h each, working in parallel).

The quantities of hydrogen to be stored on board deviate marginally from the assessment initially completed in in Ref. [16] D.2.1.4. This is a consequence that the present report conducted a deeper analysis of the power requirements during port stops, as well as for the various efficiencies and contingency margins that should be maintained.

9.6.3 Battery pack capacity

No 'safe return' capacity is required for the battery pack since ship sailing is guaranteed by diesel engine propulsion. However, adequate battery energy reserves must still be considered for the normal operation of the FC.

9.7 Preliminary electric system design

The basic configuration of the electrical power plant is given in the Principle one line diagram.

There are two main sources of electric power:

- Diesel generators
- Fuel cells and batteries

The diesel generators will be used during navigation and manoeuvring, while the fuel cells will supply the hotel loads and auxiliaries during staying in port, with the generators stopped.

Four diesel generators of 600 kW each, 3x440V, 60 Hz are provided. The generators are connected to the Main AC Switchboard, from where all the ships consumers are supplied, including the two bow thrusters, supplied trough a variable frequency drives.

One emergency diesel generator of abt. 100 kW will be installed.

For the supply of the ship consumers in port, six PEM Fuel Cells of 200 kW each are installed. The power cells are working together with a battery bank. Two battery stacks of abt. 175 kWh each are foreseen.

The total capacity of the DC el. power sources are:

- Fuel cell total nominal power: 1200 kW
- Batteries total nominal capacity: 350 kWh

The Fuel cells as well as the batteries are connected to the Main DC Switchboard trough a DC/DC converters.

During stay in port, and with all diesel generators stopped, the Main AC Switchboard will be supplied from the Main DC switchboard trough a DC/AC converters. A Power management control system should control the load flow in various operating conditions, such as manoeuvring, navigation, stay in port.

The Emergency switchboard will be in normal conditions supplied from the Main AC switchboard. In case of total black-out, the emergency generator will start automatically and supply the emergency consumers through the Emergency switchboard. From the Emergency switchboard should be supplied also the Fuel cell and Battery stack safety systems.

Operating modes

The following basic operating modes can be distinguished:

- Navigation
- Manoeuvring with bow thrusters

- Moored with all generators stopped

During navigation, two diesel generators will cover the load demand.

In manoeuvring condition, with both bow thruster in operation, three diesel generators will be in operation, while the fourth will be in stand-by.

Finished with mooring operations, all the running diesel generators will be stopped. The supply of the ship consumers will be from the fuel cells and batteries, through the DC switchboard and DC/AC converters. Prior to the generators shut-down, the generators voltage should be synchronised with the voltage coming from the inverters, in order to ensure the change over from generator to fuel cells supply without interruption.

While moored, the power demand will be practically covered with the Fuel Cells, while the batteries will cover eventual peaks loads. The batteries could be charged eighter from the fuel cells, or from the diesel generators.

The preliminary one-line diagram is shown in the picture below.

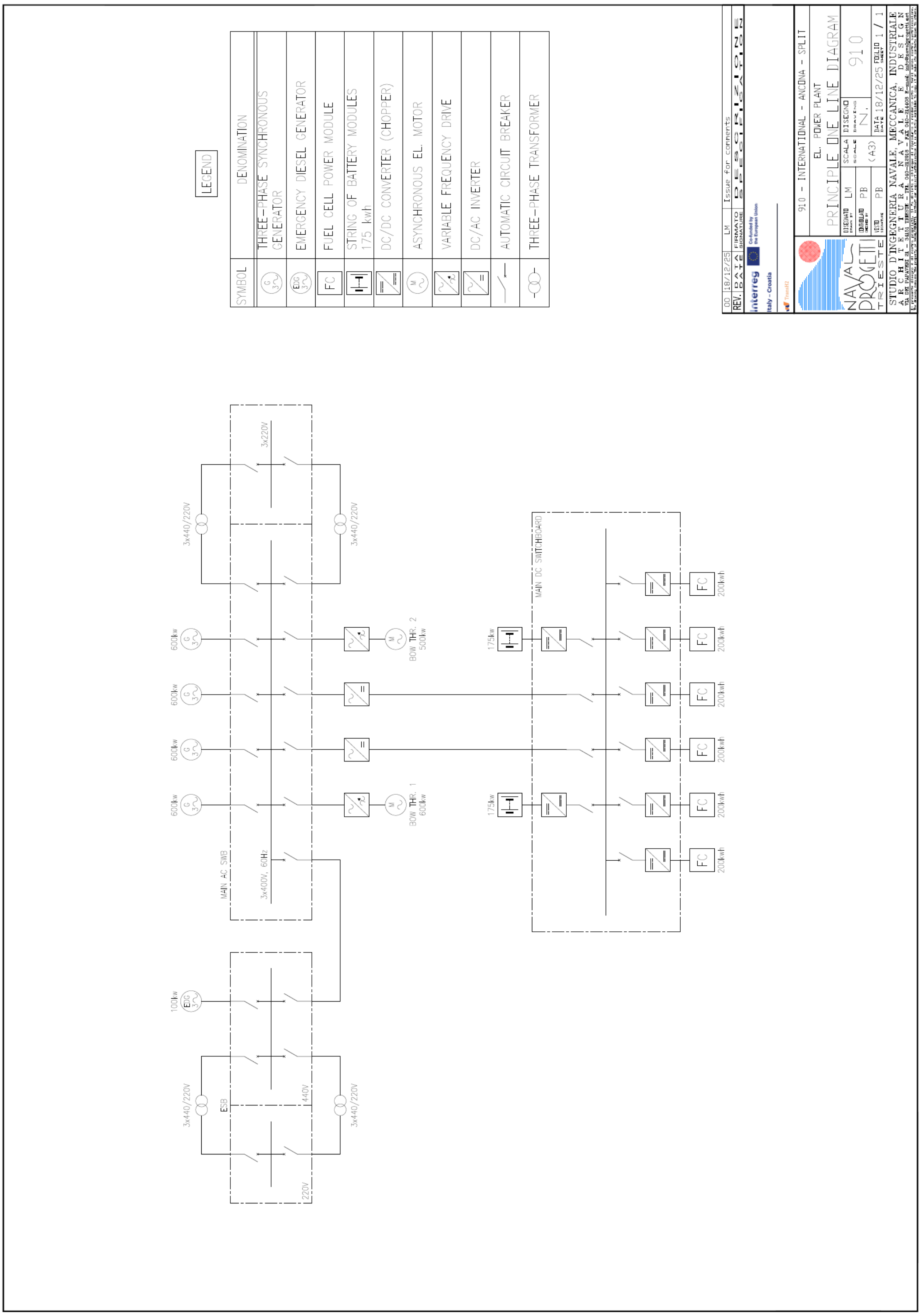


Figure 9-10: Cross-border ship electrical one-line diagram

9.8 Hazardous area plan

Hazardous area plan is shown below.

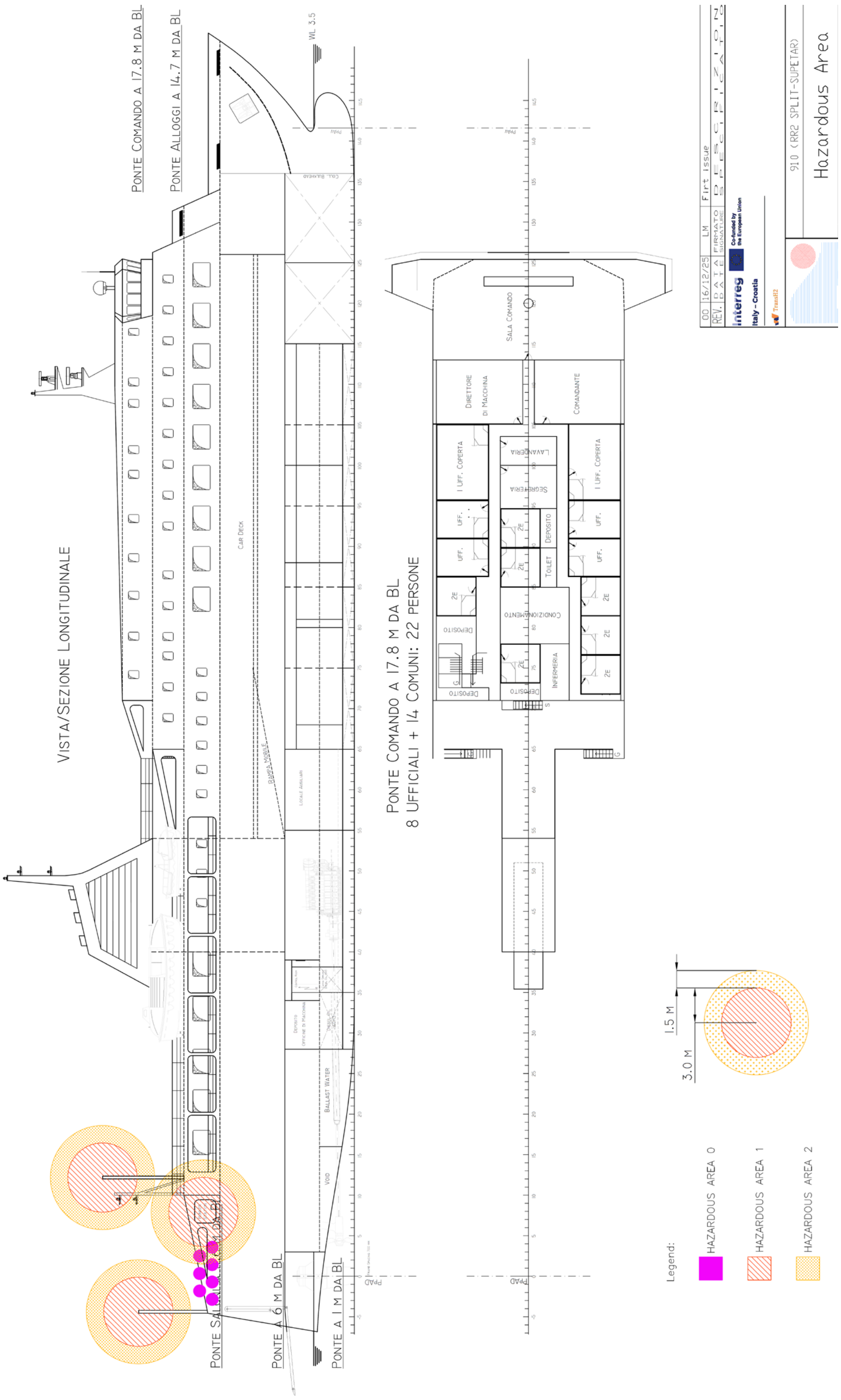


Figure 9-11: Cross-border Route ship Hazardous area plan (1)

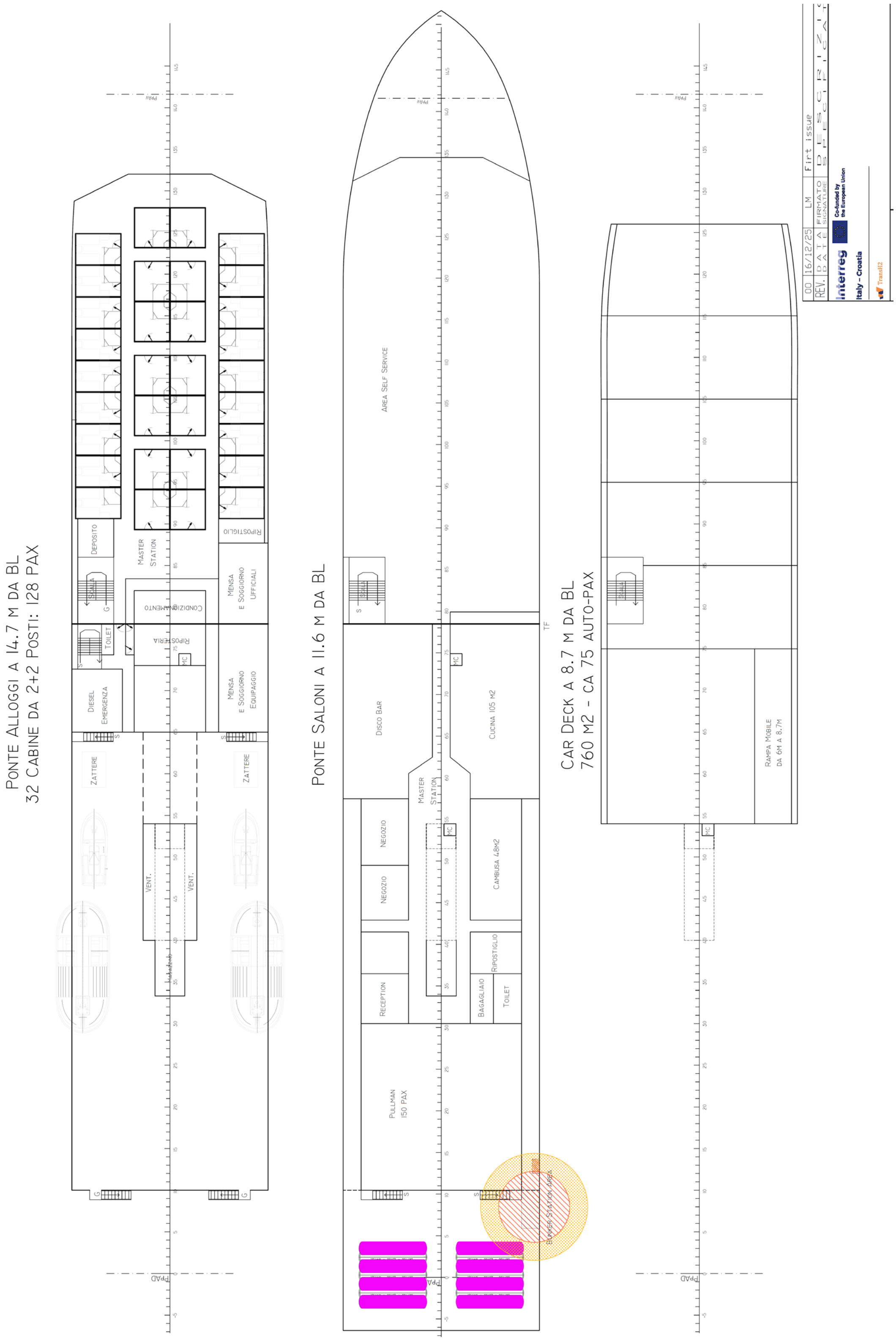


Figure 9-12: Cross-border Route ship Hazardous area plan (2)

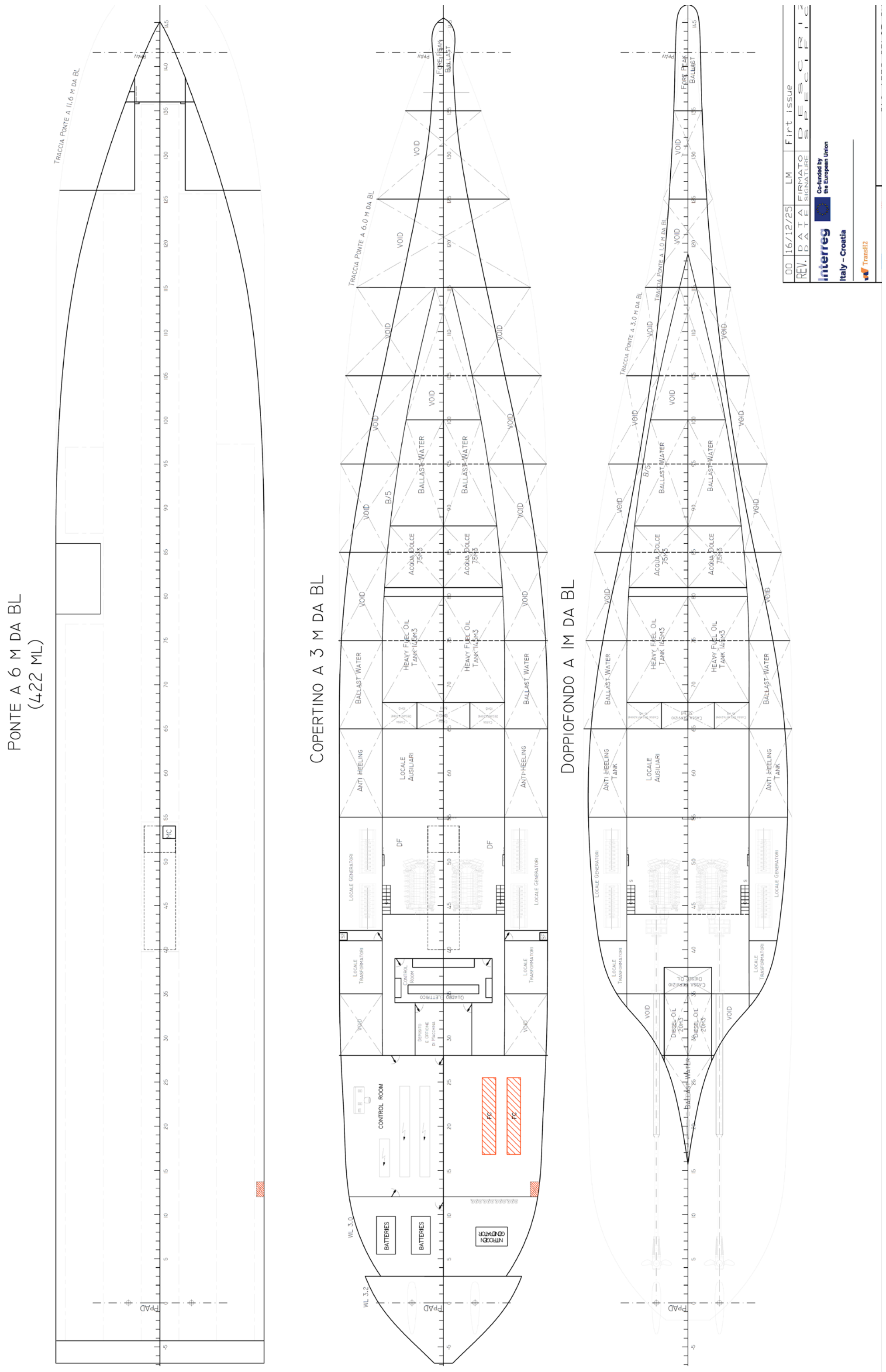


Figure 9-13: Cross-border Route ship Hazardous area plan (3)

9.9 Emergency shut down philosophy

The scope of this document is to establish basic requirements and basic functions to be adopted in the design and development of the Emergency Shut-Down (ESD) system onboard the ship provided with H2 Fuel cell and battery power system for supply of the ship in port.

The basic functions of the ESD system described in this document should be discussed and verified during Risk analysis, HAZID and HAZOP analysis and consequently modified/completed.

9.9.1 Design Criteria

The following main design criteria should be followed:

- the ESD system should be completely independent from other systems; only information exchange between ESD and other safety systems should be established.
- It shall be possible to carry out a manual emergency shutdown from the following locations as applicable:
    - wheelhouse
    - FC control room;
    - adjacent to the exit and inside of fuel cell rooms.
    - adjacent to the hydrogen storage space;
    - adjacent to the exit and inside the battery room
- The manual activation buttons shall be protected against unintended operation.
- Cables shall be fire resistant and adequately mechanical protected.
- When an emergency shutdown has been activated, automatic attempts of re-starting the machinery/equipment shall be deactivated for as long as the shut-down is activated.
- The emergency shutdown system shall be so constructed that it will fail to the conditions which are safest for the ship both in the event of signal failure and power supply failure. In case of ESD failure the system should not perform any automatic actions except failure alarm.
- The emergency shutdown system shall be protected against common mode failures and physical damage. This may be achieved by separation of equipment and appropriate physical and electrical division of the system.
- There shall be two sources of power for operation of the emergency shutdown system. In the event of failure in the regular power supply, the reserve power supply shall automatically take over.

9.9.2 ESD system architecture

The H2 storage, fuel cell and batteries ESD system consists of field mounted sensors and pushbuttons, ESD valves, dampers, trip relays, status indicators, system logic for processing of incoming signals, alarm and HMI units. The system should be able to process input signals and activate outputs in accordance with the cause and effect chart to be defined for the installation.

The ESD system shall be operated from operator stations located in Wheelhouse and FC Control Room.

The ESD system shall operate as an independent system and shall be interfaced to the other Safety systems hardwired or by redundant serial link. The ESD system actuators loop shall be normally de-energised system with loop monitoring and alarm in ECR.

The ESD system shall have hardwired interfaces for important functions, such as activation of shut down valves.

The ESD system shall be interfaced with other ship systems, eighter hardwired or via redundant serial link, as follows:

- Automation system, particularly with power management system
- Gas detection system
- Fire detection system
- Ventilation system
- H2 valves control system
- Fuel cell control and monitoring system
- Batteries control and monitoring system

Push buttons for manual shut down shall be installed on the locations as mentioned above.

There are three basic automatic functions of the Emergency shutdown system, namely:

- Shut off of hydrogen supply to Fuel cells
- Shut down of the fuel cell system
- ESD of the battery system

As a manual shutdown can be unreliable and can lead to a large gas cloud before the shutdown is performed, isolation and shutdown should be initiated automatically for hydrogen systems.

9.9.3 Gas detection

A permanently installed gas/vapour detection system shall be provided for:

- hydrogen storage space
- fuel cell spaces
- air locks
- battery room
- other enclosed spaces where gas may accumulate.

The detection systems shall continuously monitor for gas/vapour.

Detection systems for flammable products capable of measuring gas/vapour concentrations in the range 0-100% LEL shall be used.

The number of detectors in each space shall be considered taking size, layout and ventilation of the space into account, and each space shall be covered by sufficient number of detectors to allow for voting.

The detectors shall be located where gas/vapour may accumulate and/or in the ventilation outlets.

Gas/vapour detection in a fuel cell spaces and H2 cylinders space when two self-monitored detectors indicate a gas or vapour concentration of 40% LEL shall shut-down the affected fuel cell power system and disconnect ignition sources and shall result in automatic closing of all valves required to isolate the leakage. This will require that valves in the primary fuel system supplying gaseous fuel to the fuel cell space shall close automatically.

Means of manual emergency shutdown of fuel supply to the fuel cell space and de-energizing the ignition sources shall be provided inside a fuel cell space, in the FC control room and from the navigation bridge. The activation device shall be arranged as a physical button, duly marked and protected against inadvertent operation. The manual shutdown shall be handled by the ESD system and be arranged with loop monitoring.

9.9.4 Ventilation

Regarding the FC installation, there are basically two ventilation systems:

- Ventilation of the fuel cell rooms
- Ventilation of the battery room

Reduced ventilation below the required capacity shall be alarmed.

In order to verify the performance of the ventilation systems, a detection system of the ventilation flow and a monitoring system of the negative fuel cell space pressure is required. A running signal from the ventilation fan motor is not sufficient to verify performance.

Loss of ventilation in a fuel cell space shall result in an automatically shut down of the fuel cell by process control within a limited period of time. The period for the shut down by process control shall be considered on a case by case basis based on the risk analysis. After the period has expired a safety shut down shall be carried out.

9.9.5 Fire detection

An overall fire and explosion safety philosophy and strategy needs to be developed.

A fire detection system needs to consider the properties of hydrogen flames and use appropriate flame detectors, such as IR detectors.

In case of fire detection, the ESD system should also stop the ventilation so that the air supply to the rooms/cells is halted.

Fire detection is to be arranged such that the activation of any fire detectors in, or adjacent to hazardous areas or spaces containing gaseous, cryogenic liquid, toxic, corrosive or liquid fuels with a flash point below 60°C will automatically shut down any part of the fuel cell power system within or adjacent to such spaces. (LR Rule proposal 2020/01).

The lithium battery space is to be fitted with suitable fixed detectors in accordance with manufacturer's recommendations and which are capable of providing early identification of a fire or thermal runaway condition. Early identification is to include high cell temperature or detection of electrolyte solvent vapours and a combination of smoke and heat detectors.

When activated, the fire detection system is to initiate an alarm to the relevant control stations and on the navigating bridge and is to initiate the automatic isolation of electric systems within the lithium battery space, except as described below, and activate the fixed fire-fighting system.

In the event that a fire or thermal runaway condition is identified, the battery monitoring system is to initiate protective features such as automatic safe isolation of the batteries. Ventilation necessary for extraction of gases, active cooling systems, and thermal/safety monitoring and alarm are to be continued prior to, during and after an overheating or fire event. Failure of the monitoring system is to be alarmed to the ship's safety system and is to result in the battery system automatically reverting to a defined safe state.

9.9.6 Fuel cell control and monitoring system

If limit values determined for the FC control process, e.g. temperature, pressure, or voltage, which may lead to hazardous situations, the fuel cell power system is to be automatically shut down and interlocked by an independent protective device.

Typical monitoring parameters of the fuel cell that should be considered:

- cell voltage
- cell voltage deviations
- temperature exhaust gas
- temperature in FC stack
- electric current
- process air flow
- process air pressure
- cooling medium flow, level, pressure, temperature
- fuel flow
- fuel temperature
- fuel pressure
- gas detection in exhaust gas
- process water system level, pressure, purity
- parameters necessary to monitor lifetime/ deterioration.

The final list should be determined by the FC supplier.

9.9.7 Batteries control and monitoring system

The battery system shall have an integrated battery management system (BMS). The following parameters shall be measured:

- cell voltage
- cell or module temperature
- battery string current.

The BMS shall protect the battery system from the following faults by disconnection of the control switchgear:

- over-current
- over-voltage and under-voltage
- over-temperature.

The abnormal conditions to be alarmed shall as a minimum include:

- high cell or module temperature

- over- and undervoltage
- battery system disconnection
- tripping of battery breakers/contactor
- communication alarm
- cooling failure
- liquid cooling leakage
- low insulation level
- other safety protection functions

The final list will be determined by the batteries supplier.

9.10 Cost estimation CAPEX and OPEX

9.10.1 CAPEX – Cross-border route

The Capital Expenditure CAPEX estimate proposed in this section constitutes a comprehensive calculation for the ro-ro passenger ship intended for the Cross-border route service.

As outlined above, the ship will be powered by diesel engines during navigation, manoeuvring and mooring. The energy production (hotelling and auxiliary) during its stay in port will be entirely emission-free, i.e. using fuel cells and lithium-ion batteries. As a result, there will be two separate power generation plants: one diesel-driven for navigation and one zero-emission for port stays. Therefore, the capital expenditure (CAPEX) calculation will include, in addition to the traditional cost items related to a diesel-powered ro-ro pax ferry, the costs related to zero-emission energy production (port stay only).

Given the pioneering nature of the project and the limited availability of analogous case studies, it is recommended to adopt a contingencies-based approach, since the premium over conventional diesel electrical generation during port stops is indicative of the emerging technology status of marine fuel cells and hydrogen infrastructure. The proposed CAPEX calculation takes into account also an appropriate accuracy range, based on the project level of definition as suggested by AACE (ref. AACE International Recommended Practice No. 18R-97). The maturity level of the design achieved and the novelty of the technological choices proposed suggest a Class III accuracy rating, as illustrated in the figures below.

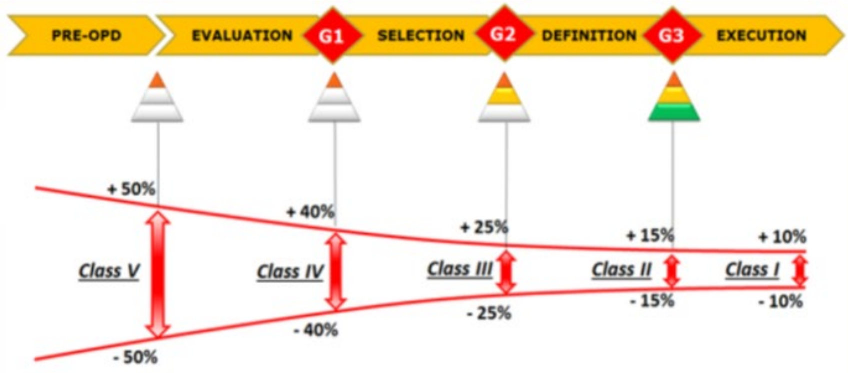


Figure 9-14: Project Development diagram

	Primary Characteristic	*Secondary Characteristic*		
ESTIMATE CLASS	**MATURITY LEVEL OF PROJECT DEFINITION DELIVERABLES** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]
Class 5	0% to 2%	Concept screening	Capacity factored, parametric models, judgment, or analogy	L: -20% to -50% H: +30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: -15% to -30% H: +20% to +50%
Class 3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	L: -10% to -20% H: +10% to +30%
Class 2	30% to 75%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: -5% to -15% H: +5% to +20%
Class 1	65% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: -3% to -10% H: +3% to +15%

Notes: [a] The state of process technology, availability of applicable reference cost data, and many other risks affect the range markedly. The +/- value represents typical percentage variation of actual costs from the cost estimate after application of contingency (typically at a 50% level of confidence) for given scope.

Table 9-11: Level of definition as suggested by AACE classification

The following main assumption has been made:

- Hull construction cost at approx. 6 Euro/kg
- Pricing for fuel cells 3000 Euro/kW, with prices expected to decrease in the coming years
- Current Li-ion battery costs 800 Euro/kWh, with prices expected to decrease in the coming years
- First-of-type ship with no series discount

In the light of the above the CAPEX has been estimated in 59M Euro.

Finally, it is important to note that potential funding sources could be considered under the EU's Connecting Europe Facility, the state maritime fund for green shipping, the regional development funds and green shipping loans with favourable rates.

This 59M Euro CAPEX represents a comprehensive, technically detailed estimate for a pioneering hydrogen-electric ro-ro passenger ship for cross-border service. The cost reflects the mature technologies (as hull, propulsion, navigation) the emerging technologies (as the fuel cells and the hydrogen systems). The premium over conventional electrical generation is justified by zero local emissions, future-proof technology, potential operational savings (fuel, maintenance), regulatory compliance with emerging EU standards, potential subsidy capture. It is anyway recommended to proceed with detailed engineering phase to refine critical system specifications and confirm supplier pricing for long-lead items (fuel cells, hydrogen cylinders and Li-ion batteries)

The CAPEX calculation is presented in the following Table 9-12.

CAPEX for Cross-border Route	**Weight**	**Material cost**
	[t]	[Euro]
1 - Steel structure	864.4	1 780 000
2 - Hull completion	98.0	1 580 000
3 - Hull equipment	333.0	5 440 000
4 - Hull & engine room auxiliaries	167.0	3 670 000
5 - HVAC and insulation	80.0	2 310 000
6 - Electric equipment	64.0	3 230 000
7 - Catering	13.0	770 000
8 - Cabins	78.0	1 650 000
9 - Public areas	74.0	3 060 000
10 - Propulsion system	178.0	6 800 000
11 - Fuel cells system 1200 kW	9.5	3 600 000
12 - Li-ion battery system 350 kWh	4.9	280 000
13 - H2 storage system @ 350 bar - 1689 kg H2	44.2	2 649 240
Material total cost	2 008.0	36 819 240
Labour total cost		10 010 000
Total		46 829 240
Classification & Certification		1 400 000
Engineering & Design		3 280 000
Shipyard Costs & Project Management		2 340 000
Commissioning		1 870 000
Shipyard Profit		2 340 000
Contingency		1 400 000
TOTAL SHIP CAPEX		59 459 240

Table 9-12: CAPEX Summary table

The Fuel Cell System and the H2 storage system represent the most significant equipment cost at 8M Euro and is a prime example of cutting-edge marine technology. The cost of hydrogen storage is also high due to the use of marine-certified composite cylinders and the stringent safety requirements that must be met.

The classification costs are elevated due to the innovative nature of hydrogen electrical generation. This is because the classification societies, as a general rule, have limited precedent in this area.

The state-local factors must also be taken into account: depending on the shipyard selected, construction in Italy/Europe may vary by ±30%.

The battery system does not have a significant cost nor large storage capacity as it has been designed and sized mainly for the FC management.

The H2 power generation system premium cost can be considered to be approx 10M Euro (ship only) and 13M Euro including the shore infrastructures (Ancona shore-based refuelling facilities).

The CAPEX in this section differs slightly from the initial assessment completed in Ref. [16] D.2.1.4: the present report's findings are based on a more thorough examination of the present costs for various items of the lightship.

For details about shore-based refuelling station CAPEX see Ref.[19] and [20].

9.10.2 OPEX – Cross-border route

The OPEX (Operating Expenditure) calculation outlined in this section provides a comprehensive representation of the current annual operating costs required to manage the innovative hydrogen-electric ferry intended for the Cross-border route service, including but not limited to salaries, fuel, maintenance, administration, etc. The calculation concerns the annual operations of a single ship.

As mentioned in the previous section, the proposed OPEX calculation takes into account an appropriate accuracy range, based on the project level of definition as suggested by AACE.

The following main assumption has been made:

- It has been estimated that the cost of refuelling with H2 will be €10 per kilogram, plus the fixed costs for the shore-based station. It is anticipated that prices will decrease in the coming years.
- The cost of extraordinary maintenance of the fuel cell stack is estimated to be 40% of the FC CAPEX, to be amortized over seven years.
- The cost due to the battery degradation is estimated to be amortized over seven years.
- The personnel costs are based on a requirement for six members per shift, across two shifts.
- The ship service days in the year are 240.

In the light of the above the annual OPEX has been estimated in 14M Euro, as detailed in the following Table 9-13.

CROSS-BORDER Route ANCONA-SPLIT		
OPEX calculation (Annual)		OPEX
No. of working days in the year: 240		[Euro]
No. of ship in the fleet: 1		
1	Fuel oil consumption	1 540 000
2	Hydrogen consumption	4 490 000
3	Electricity consumption (from shore connection)	0
4	Crew, 25 people, three shifts	4 880 000
5	General maintenence & repairs	370 000
6	Drydocking allowance	450 000
7	Insurance	610 000
8	Administrative	450 000
9	Port fees	500 000
10	Classification Society & Flag State	180 000
11	Provisions & Stores	400 000
12	Environmental ETS	500 000
13	Miscellaneous	500 000
14	FC stack major overhul	210 000
15	FC standard maintenence	60 000
16	Battery degradation	40 000
17	Battery standard maitenance	10 000
OPEX total		13 650 000

Table 9-13: OPEX Summary table

Despite the relatively high OPEX calculated value compared to a traditional diesel electric generation plant, the following pros have to be considered:

- Zero emissions (regulatory compliance) when moored at port
- Future-proof technology
- H2 prices expected to decline 40-50% by 2030
- Potential subsidies/incentives for green ships
- Enhanced corporate image & passenger appeal

The annual OPEX reflects the operating costs of a cutting-edge, zero-emission, hydrogen-electric generation system for Cross-border service which are higher than those of conventional diesel alternatives. This premium is primarily driven by the cost of hydrogen fuel. However, as green hydrogen production scales up and costs decline in the coming years, the operational cost gap will narrow significantly, potentially reaching parity with diesel while maintaining zero emissions. Investing in this technology will establish the operator as a leader in sustainable maritime, offering long-term economic and environmental benefits.

This analysis is based on market conditions and technology in 2025. Actual costs may vary based on supplier negotiations, regulatory changes and operational experience.

Crew costs dominate OPEX and are strongly dependent on national wage levels, union agreements and whether the operation is public or private. For the cross-border ferry with 500 passengers in EU waters, crew might include master, chief engineer, six officers, six deckhands/AB, purser and ten accommodation personnel. The manning level will comply with flag-state safe manning.

It is important to note that capital expenditure depreciation has not been included in operating expenses because it is a long-term investment that is capitalised and depreciated in the income statement over time, in contrast to operating expenses.

The potential government subsidies PSO (EU/Italian grants for zero-emission ships) have not been included in the OPEX calculation.

It is pertinent to acknowledge the role of the PSO (public service obligation) in this context. The PSO is a financial contribution made by a government to support essential public transport or public utility services that are often unprofitable. These services may encompass renewable energy initiatives that are not typically offered by the market. The fundamental purpose of the subsidy is to guarantee that social benefits, including connectivity and green energy, are accessible to the general public. This state aid, which is a common occurrence within the European Union, guarantees the provision of essential services. The overarching objective of these regulations is twofold: firstly, to prevent market distortions, and secondly, to achieve a balance between public needs and commercial viability through subsidies to operators.
The OPEX in this section differs slightly from the initial assessment completed in Ref. [16] D.2.1.4: the present report's findings are based on a more thorough examination of the present costs for various items included in OPEX.

For details about shore-based refuelling station OPEX see Ref.[19] and [20].

9.11 3D model

Below are shown some pictures of the 3D model of the ship.

Figure 9-15: Cross-border 3D model (1)

Figure 9-16: Cross-border 3D model (2)

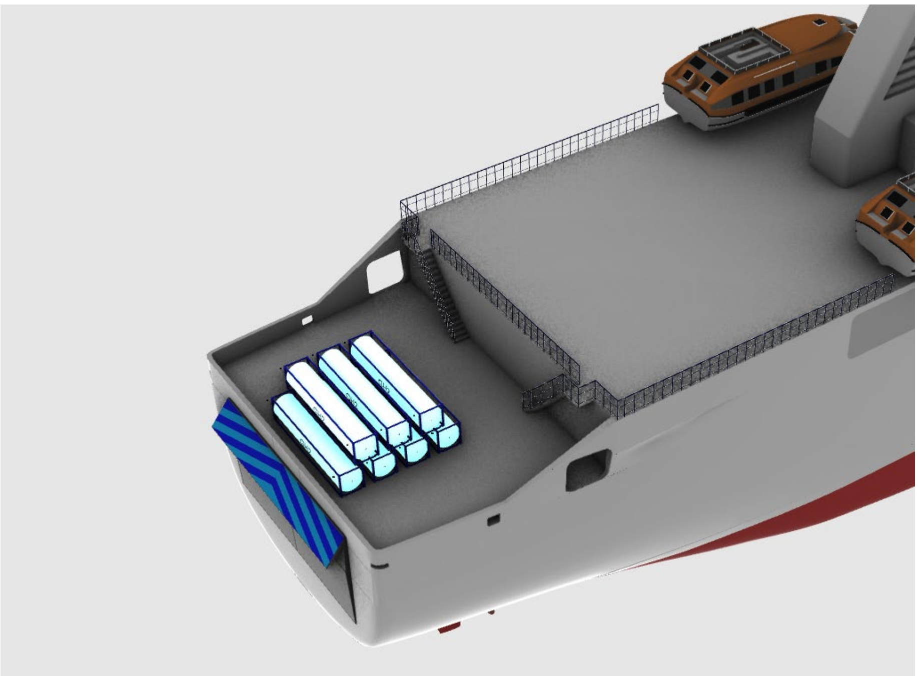


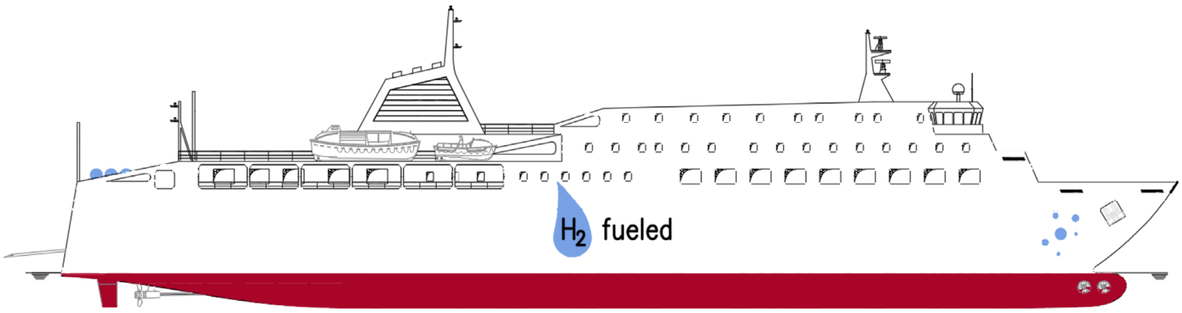
Figure 9-17: Cross-border 3D model with details of the hydrogen storage tanks in the hull

9.12 Power Point presentation

INTERREG_TransH2_Cross-border.pdf

9.13 Leaflet

CROSS-BORDER ROUTE RO-RO PAX



SHIP MAIN CHARACTERISTICS	
Ship Type	Ro-Ro Passenger Ferry
Max cars / truck lane	75 / 400 m
Max POB	520
Length Over All	111.0 m
Length B.P.	99.0 m
Breadth (mld)	16.5 m
Depth	6.0 m
Design Draught	3.5 m
Service Speed	21.0 kn
Displacement @3.5 m	abt. 3200 t

PROPULSION SYSTEM	
Power generation	PEM FC 1200 kW & Li-Ion Battery 350 kWh
Propulsion	Wartsila 12V26A, 2 x 3720 = 7 440 kW
H2 Storage	n. 14 Type III pressure vessels abt. 5100 litres each
Endurance	1300 nm @21 kn

Figure 9-18: Cross-border ship leaflet

10 Conclusions

10.1 General

This deliverable encompasses two types of analysis: the first for regional routes and the second for cross-border routes. It provides three conceptual ship designs that address the following:

- Regional ro-ro pax connections for Croatian route, full electric
- Regional ro-ro pax connections for Italian route, full electric
- Cross-border ro-ro pax connection, hybrid

assessing technical implications and first-order cost drivers for hydrogen-based solutions.

For the regional use cases, the proposed architecture based on compressed gaseous hydrogen (H_2) at 350 barg, PEM fuel cells and Li-ion battery energy storage supports the objective of zero-emission operation over short, repetitive routes, subject to the boundary conditions and assumptions defined in the report.

For the cross-border use case (Ancona–Split), the analysis indicates that a fully zero-emission propulsion concept would require energy and power levels that are not considered achievable within the current technology and integration constraints identified (e.g., FC power order of magnitude and associated storage/bunkering requirements). The adopted concept therefore focuses on zero-emission power generation during port stays, while propulsion remains diesel-based during navigation.

10.2 Design results

10.2.1 Regional routes

The two regional route concept design have been tailored for the following route:

- Croatian regional route connecting:	Split - Supetar
Distance in nautical miles:	8.6
Service speed in knots:	11
Azimuth thrusters total nominal power in kW:	1000
Number of trips in a operative day:	14
Range in nautical miles:	60
Fuel Cells nominal power in kW:	1200
Li-ion battery nominal capacity in kWh:	700
Number of GH_2 cylinders:	7

- Italian regional route connecting: Tronchetto - Lido
  Distance in nautical miles: 3.8
  Service speed in knots: 6
  Azimuth thrusters total nominal power in kW: 350
  Number of trips in a operative day: 20
  Range in nautical miles: 38
  Fuel Cells nominal power in kW: 360
  Li-ion battery nominal capacity in kWh: 350
  Number of GH_2 cylinders: 3

The two regional concepts are differentiated primarily by installed propulsion power and required range, resulting in changes to fuel-cell installed power, battery capacity and number of GH_2 cylinders, while maintaining the same overall vessel characteristics:

The selected storage approach (Type III composite cylinders at 350 barg, length 5.7 m external diameter 1.1 m) and the refuelling concept (baseline two refuelling operations per day) are consistent with the operational assumptions applied.

10.2.2 Cross-border route

The cross-border route concept design has been tailored for the following route:

- Cross-border route connecting: Ancona - Split
  Distance in nautical miles: 130
  Service speed in knots: 20
  Diesel propulsion total nominal power in kW: 7 440
  Number of trips in a operative day: 1
  Range in nautical miles: 1300
  Fuel Cells nominal power in kW: 1200
  Li-ion battery nominal capacity in kWh: 350
  Number of GH_2 cylinders: 14

The report concludes that a port-stay-only zero-emission concept is technically more proportionate to the current constraints than a fully hydrogen-propelled solution for navigation, due to the power/energy and logistics implications of the latter.

The analysis identifies fuel supply logistics and the associated cost premium as key limiting factors for cross-border feasibility under present conditions.

10.3 H_2 fuel cost

The hydrogen price basis was verified against January 2026 market information obtained from suppliers, with the explicit note that prices may be volatile. Current forecasts suggest that costs should be substantially reduced in the next years. The economic conclusions should therefore be interpreted within a scenario framework (e.g., sensitivity to delivered hydrogen price and bunkering utilisation).

10.4 State contributions

The CAPEX and OPEX estimates do not include potential public support mechanisms (e.g., PSO-type contributions and/or grants for zero-emission vessels and related infrastructure). If such measures become available and applicable, they may improve the overall feasibility compared to the baseline economic case presented in this deliverable.

10.5 Further investigation

To increase robustness and improve feasibility, the following follow-up activities are recommended:

1. Explore the regional-route refuelling concept with the objective of reducing refuelling frequency to once per day, subject to operational constraints and required reserves.
2. Monitor the technological advancements pertaining to the flow rate capabilities of shore-based refuelling stations. These innovations have the potential to significantly reduce refuelling times, thereby enhancing the operational efficiency of vessels.
3. Investigate into alternative GH2 storage modularisation is suggested in order to ascertain the future market potential for larger-capacity GH2 cylinders in terms of both size and pressure. This will reduce the cylinders number, the system complexity and the interfaces.
4. Progress the approval pathway through structured risk-based work (e.g., HAZID/HAZOP/QRA and interface definition for bunkering), aligned with flag/Class expectations for hydrogen systems and bunkering arrangements.
5. Refine the cost basis through vendor-backed quotations for long-lead items (fuel cells, cylinders, batteries) and update uncertainty/contingencies consistently with the maturity of the concept design.