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## **Analysis of Ropax Short Sea Shipping Vessels in the Light of Directive (EU) 2023/959**

### **Abstract**

In an effort to reduce GHG emissions, coastal shipping operators are undertaking various activities to contribute to the reduction of fossil fuel consumption and greenhouse gas emissions during the transition to environmentally friendly propulsion systems, all without compromising their regular operations. Although alternative fuel technologies are not yet fully implemented, the authors have developed a hypothetical model based on empirical data to compare current fuels with those expected to be available in the near future. Short sea shipping operators face potentially high transition costs as they shift to eco-neutral fuels, alongside the continuous goal of reducing their carbon footprint. This paper analyzes a RoPax vessel used on the Prizna-Žigljen route to assess the retrofit process for a zero-emission propulsion system. Two suitable solutions for this route are explored: (1) battery systems and (2) proton-exchange membrane fuel cells (PEMFC), to identify the most advantageous technology for implementation on the vessel. Various aspects are considered, including the ferry's daily schedule, available volume and space, propulsion power requirements, necessary energy storage or fuel tank capacity, cost-efficiency, and more. This multi-faceted analysis ultimately identifies hydrogen-powered PEMFC as the optimal clean energy system, offering the most suitable retrofit solution for this specific case study to ensure CO<sub>2</sub>-free travel.

**Keywords:** RoPax vessels, zero emissions, hydrogen fuel cells (PEMFC), energy transition

## 1. Introduction

The maritime sector is a significant contributor to greenhouse gas (GHG) emissions, producing approximately 1,076 million tons in 2018, accounting for about 3% of global emissions. Although most of these emissions originate from large transoceanic cargo vessels, emissions from short-sea shipping play an important role on a local level, particularly due to passenger transport on Roll-on/Roll-off passenger (RoPax) vessels (Bukša J. , 2005). According to the Fourth IMO GHG Study (IMO, 2021), Ferry-RoPax vessels contributed approximately 37 million tons of CO<sub>2</sub> emissions in 2018 (out of a total 1,056 million tons for the entire maritime sector). These vessels typically consume more fuel per unit of transport work due to specific speed profiles and the balance between cargo and passenger needs. Nonetheless, short-sea shipping and RoPax vessels have so far received relatively limited attention in scientific research focused on reducing GHG emissions in the maritime sector (Mayanti, Hellström, & Katumwesigye, 2024).

Decarbonization typically requires significant capital investment for shipowners, whether through retrofitting existing vessels or replacing them with environmentally friendly ships. This makes such changes challenging for owners and operators in a regulatory environment that is continuously evolving. Additionally, there is considerable uncertainty regarding the cost of alternative fuels, which have the greatest potential to reduce greenhouse gas emissions.

The prediction is based on an analysis of a RoPax vessel operating on the short route between Prizna - Žigljen and vv., aiming to assess the retrofit process for zero-emission propulsion systems. The study considers two different solutions: 1) battery systems and 2) proton-exchange membrane fuel cells (PEMFC). Previous studies, (Elkafas, Rivarolo, Barberis, & Massardo, 2023), have also analyzed solid oxide fuel cells (SOFC) and fuels such as hydrogen, ammonia, natural gas, and methanol, which were deemed less suitable for this route due to various factors, including the ferry's daily operational requirements and schedule, available space, necessary propulsion power, energy or fuel storage capacity, and economic feasibility.

The introduction also includes a list of abbreviations and symbols used throughout the study.

Table 1 - List of Abbreviations and Symbols

Abbreviations	Description	Variables	Description
BoP	Balance of plant	CapEx	Capital expenses (EUR)
CAI	Cost-assessment indicators	CF	Cost factor (EUR/kW or EUR/kWh or EUR/kg-fuel)
CO <sub>2</sub>	Carbon dioxide	d	Discount rate (%)
DC	Direct current	E	Electricity energy generated (kWh)
DNV	Det Norske Veritas	EC	Energy capacity (kWh)
ETS	Emission trading system	ECC	Energy carrier consumption (kWh)
EU	European Union	f	Extra factor for the supplementary equipment (-)
FC	Fuel cell	FM	Fuel mass (kg)
FPP	Fixed-pitch propellers	GD	Gravimetric density (kW/kg)
GHG	Greenhouse gases	HEC	Heating up energy capacity (kWh)
IMO	International Maritime Organization	HEF	Heating up energy factor (kWh/kW)
LCOE	Levelized cost of energy	J	Number of one-way trips (-)
LNG	Liquefied natural gas	LHV	Lower heating value (kWh/kg)
MAC	Marginal abatement cost	LT	Lifetime (years)
MARPOL	International Convention for the Prevention of Pollution from Ships	n	Number of years (year)
MDO	Marine diesel oil	N	Number of replacements (-)
MeOH	Methanol	P	Rated power of fuel cell (kW)
NO <sub>x</sub>	Nitrogen oxide	OpEx	Operating expenses (EUR)
NPV	Net present value	T	Operational time [hour]
OWT	One-way trip	V	Volume (m <sup>3</sup> )
PEMFC	Proton exchange membrane fuel cell	VD	Volumetric density (kW/m <sup>3</sup> )
PM	Particulate matter	VoyEx	Voyage expenses (EUR)
ROI	Return on investment	W	Weight (kg)
R&D	Research and development	XH	Hydrogen content in ammonia (%)
SOFC	Solid oxide fuel cell	Y	Number of battery cycles (-)
SO <sub>x</sub>	Sulfur oxide	Z	Lifetime of fuel cell (hours)
		η	Efficiency (%)

Subscripts	Description		
ann	Annual		
BC	Battery cycles		
BT	Battery		
cps	Clean power system		
cr	Cracker		
DP	Diesel-powered system		
ec	Energy carrier		
em	Electric motor		
f	Fuel type		
FC	Fuel cell		
fss	Fuel storage system		
oc	Other components		
OM	Operational mode		
pce	Power conditioning equipment		
ps	Power system		

## 2. Background

This study is based on the Regulations and Directives of the European Parliament and Council governing CO<sub>2</sub> emissions monitoring in maritime transport, with a particular focus on the emissions trading system, details of which are chronologically listed below.

REGULATIONS	SUMMARY
Regulation (EU) 2015/757	on the monitoring, reporting, and verification of greenhouse gas emissions from maritime transport, and amending Directive 2009/16/EC (European Parliament and the Council of the European Union, 2015). A system for monitoring, reporting, and verifying greenhouse gas emissions in maritime transport was established to extend the reduction of international maritime emissions to the level of the European Community. Regulation 2015/757 is considered the initial phase of the European Community's maritime sector contribution to fulfilling the obligations of the Paris Agreement and achieving the European Green Deal's climate neutrality goals by 2050 (EC, 2020).

Directive (EU) 2023/959 of the European Parliament and of the Council of 10 May 2023	amending Directive 2003/87/EC establishing a greenhouse gas emissions trading system within the Union and Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union's greenhouse gas emissions trading system ( European Parliament and of the Council, 2023).
Annex 1 of Directive 2023/959	stipulates that the carbon dioxide emissions trading system includes ships of 5,000 gross tonnage and above in regard to emissions released during their voyages for the transport of cargo or passengers for commercial purposes. This applies from their last port of call to a port under the jurisdiction of a Member State, and from a port under the jurisdiction of a Member State to their next port of call, as well as within ports under the jurisdiction of a Member State as of January 1, 2024. The implementation will be phased in as defined in Article 3gb of Directive 2023/959: by September 30, 2025, shipping companies are required to surrender 40% of verified emissions reported for 2024; by September 30, 2026, 70% of verified emissions reported for 2025; by September 30, 2027, 100% of verified emissions reported for 2026; and, thereafter, for each subsequent year by September 30 of the current year for the previous year.
Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport	The aim is focused on increasing the use of renewable and low-carbon fuels and alternative energy sources in maritime transport, limiting the greenhouse gas intensity of energy used on ships that enter, stay in, or depart from ports under the jurisdiction of a Member State, and mandating the supply of shore-side electricity or the use of zero-emission technology for ships while at berth in ports under Member States' jurisdiction ( European Parliament and of the Council, 2023).

<p>Proposal to amend Regulation 2023/1805</p>	<p>It is anticipated that if the International Maritime Organization adopts a global standard for greenhouse gas emissions from fuels or global limits on the greenhouse gas intensity of energy used on ships, the Commission will promptly submit a report to the European Parliament and the Council. This report will assess the measure's ambition in relation to the Paris Agreement goals and its overall environmental integrity, as well as the alignment of Regulation 2023/1805 with the global measure, including the need to avoid double regulation of greenhouse gas emissions from maritime transport at both the Union and international levels.</p>
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In maritime transport, emissions refer to the release of greenhouse gases from ships during their operations. The Emissions Trading System (EU ETS) is based on the gradual reduction of available emission allowances. According to Directive (EU) 2023/959, the total number of emission allowances at the EU level will be reduced by 90 million in 2024 and by an additional 27 million in 2026. With the inclusion of maritime transport in the EU ETS, an increase of 78.4 million emission allowances is projected for this sector in 2024, applying a linear reduction factor of 4.3% annually from 2024 to 2027, and 4.4% from 2028 onwards.

From January 1, 2026, and January 1, 2027, the amount of emission allowances will increase to account for the inclusion of non-CO<sub>2</sub> greenhouse gas emissions from maritime transport, as well as emissions from coastal vessels, based on data from the most recent available year.

This additional amount of emission allowances will be allocated to the Innovation Fund to support innovative technologies and infrastructure, including the production of low- or zero-carbon fuels. The aim is to facilitate the decarbonization of maritime, air, rail, and road transport, supporting projects that contribute to emission reductions in the maritime sector, the electrification of maritime transport, and the mitigation of its full climate impact (European Parliament, 2023).

Within the framework of existing regulations and efforts to reduce greenhouse gas emissions from ships, short-sea shipping operators are soon to be faced with a clear decision: either accept penalties for their carbon footprint and participate in the emissions trading system or invest in alternative fuels and propulsion systems. In this paper, alternative solutions refer to fuel cells (FC) and pure battery systems. Both approaches use electric propulsion systems powered by electricity from "clean" energy sources.

## 2.1. Literature review

A significant body of scientific and professional literature, thematic conferences, and legal regulations has been dedicated to the use of low- or zero-emission greenhouse gas (GHG) fuels as a response to increasingly evident climate change. The goal of these initiatives is to reduce and eliminate the carbon footprint. Maritime transport, like aviation, has long enjoyed a privileged status with weaker regulations and fewer penalties. A thorough analysis of alternative propulsion systems in short-sea shipping has been covered in studies (Bukša, Bukša, & Nikolić, 2022), (Sopta, Bukša, Bukša, & Peronja, 2020), (DNV GL – Maritime, 2020) and reports (DNV-GL, 2020).

Hosseini and Butler (2019), Martins and Brito (2020), and Shusheng et al. (2020), examined the potential of hydrogen as a propulsion fuel in detail, while Tronstad et al. (2017), made a key contribution to understanding the application of fuel cells (FC) in maritime transport. The application of fuel cells and batteries in short-sea shipping has not yet attracted significant interest from the scientific and professional community, mainly due to the lack of penalties for fossil fuels, which has reduced accountability among shipping operators. However, the adoption of EU Directive 2023/959 (European Parliament, 2023), has sparked growing interest in this topic. This study draws on the experiences of Mayantia, Hellström, and Katumwesigya (2024), as well as the templates of Elkafas et al. (2023), which served as the basis for a hypothetical calculation of the cost-effectiveness of replacing the current propulsion fuel of a RoPax vessel with fuel cells or batteries for generating the electricity needed to power electric motors.

## 3. Research Methodology

The analysis of the potential of Ro Pax vessels for short-sea shipping in the context of Directive (EU) 2023/959 is conducted through two aspects. The first aspect involves calculating greenhouse gas emissions, while the second focuses on a case study, using the example of the Ro Pax vessel “Cres” in short-sea shipping.

### 3.1. Emissions Calculation

The European Union has decided to include the maritime sector in its Emissions Trading System (EU ETS) from 2024, covering all intra-European maritime journeys and 50% of extra-European journeys. This step aims to encourage the reduction of greenhouse gas emissions in maritime transport. In the short term, the costs associated with the EU ETS are expected to be passed on to transport users through additional fees. If these increased costs are not adequately addressed, there is a risk of “carbon leakage,” where emissions could be redirected to less regulated sectors or regions. Additionally, in the roll-on/roll-off (RoRo) and roll-on/roll-off passenger (Ro Pax) segments, due to direct competition with road and rail transport and the relative ease

of switching to other transport modes, there could be a modal shift away from maritime transport towards these alternatives.

Research on greenhouse gas (GHG) emissions calculation is crucial for short-sea shipping (SSS) operators, considering the future period when GHG emissions will be subject to penalties. For this calculation, it was necessary to gather data on total annual fuel consumption to calculate the parameters required by MRV (2024). Total emissions can be estimated based on fuel consumption and the emission factor (EF), as shown in equation (1).

$$EM_i = \sum EF_i^f \cdot Q_f \quad (1)$$

Here, EM represents the total emissions of component i, EF denotes the emission factor for fuel f, and Qf denotes the quantity of fuel f consumed. For reporting Ro Pax vessel emissions, an additional step is included in which total emissions are appropriately allocated between passengers and cargo. This allocation can be carried out using either the mass or the area method, each yielding different results. In this study, mass allocation was applied, which is widely used when reliable data is available. The mass calculation is based on the number of passengers, their vehicles (such as cars, caravans, buses), and the total cargo weight (e.g., trailers). Mass allocation is presented in equations (2) and (3).

$$Al_p = \frac{Pax.m_p + C.m_c + B.m_b}{Pax.m_p + C.m_c + B.m_b + T.m_t} \quad (2)$$

$$Al_c = \frac{T.m_t}{Pax.m_p + C.m_c + B.m_b + T.m_t} \quad (3)$$

In this analysis,  $Al_p$  and  $Al_c$  represent the mass allocation for passengers and cargo. The symbols Pax, C, B, and T represent the annual number of passengers, cars, buses, and trailers. Weights of passengers with luggage, cars, buses, and trailers are denoted as  $m_p$ ,  $m_c$ ,  $m_b$ , and  $m_t$ .

For calculating carbon emissions based on annual fuel consumption (MDO), there are three different carbon tax schemes: the Stated Policies Scenario (STEPS), the Sustainable Development Scenario (SDS), and the Net Zero Emissions Scenario (NZE), as shown in the following table.

Table 2 - Carbon price in different years (€/t-CO<sub>2</sub>)

Tax scheme	2030	2050
STEPS	57.5	79.6
SDS	106.1	176.8
NZE	114.9	221

Source: Mayanti, Hellström, & Katumwesigye, 2024

Costs are calculated using the equation:

$$Cost = F \cdot F_p + C \cdot C_p \quad (4)$$

where F and F<sub>p</sub> are fuel consumption (tons) and fuel price (€/ton), while C and C<sub>p</sub> are CO<sub>2</sub> emissions (tons) and carbon price (€/t-CO<sub>2</sub>).

### 3.2. EU Emissions Trading System (ETS)

The EU ETS, introduced in 2005, is a market-based mechanism (MBM) through which the EU regulates and reduces overall emissions in covered sectors. This system requires all participants to hold or purchase European Union Allowances (EUA) to cover all of their emissions. The EU sets a cap on the total allowable amount of emissions, while market demand subsequently determines the price at which participants can sell or buy EUAs to cover their emissions. As part of the “Fit for 55” package, the EU has decided to include the maritime sector in the EU ETS. On April 18, the European Parliament, and on April 25, 2023, the Council, approved the revised Directive, which came into effect on January 1, 2024. This change is expected to have a significant impact on the maritime sector, particularly regarding costs associated with various types of fuels, as it will increase the prices of greenhouse gas-emitting fuels.

From 2024 onward, the Directive will apply to cargo and passenger ships over 5,000 GT calling at EU ports, covering verified carbon dioxide emissions for commercial voyages. From 2027, it will also extend to offshore ships over 5,000 GT, including emissions of carbon dioxide, methane, and nitrous oxide. Unlike previous practices in other sectors, the EU will not allocate free emission allowances; however, a phased approach will allow shipowners to adapt to the new regulations. Thus, in 2024, 40% of emissions will be covered, rising to 70% in 2025 through EUAs. From 2026 onward, all relevant emissions requirements must be covered by EUAs by shipowners (Bureau Veritas Marine & Offshore, 2023).

Relevant emissions will be monitored under the EU framework for Monitoring, Reporting, and Verification (MRV). Currently, the EU MRV documents only CO<sub>2</sub> emissions, but from 2024, it will expand to include methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O). Starting in 2026, methane and nitrous oxide emissions will also be included in

the EU ETS for shipping, and shipowners will be required to cover them with EUAs.

To facilitate the inclusion of the maritime sector in the EU ETS, 78.4 million emission allowances will be added to the total EUA amount in 2024. From 2024 to 2027, the EUA cap will decrease by 4.3% annually, and from 2028 onwards, by 4.4% annually (ibid.). Allowances will be sold through a central auction and traded on the European Energy Exchange (EEX). Revenues from the sale of 20 million EUAs will be collected in the Innovation Fund, aimed at vessel renewal<sup>1</sup>, while the remaining revenue will be distributed among EU member states (Borgstrøm & Haufe, 20223). Floden et al. (2024) summarized the key insights into EU ETS policy:

- The integration of the maritime sector into the EU ETS represents an important step in reducing greenhouse gas emissions in this sector, along with further reductions in NOX, SOX, and particulate matter (PM) emissions.
- CO<sub>2</sub> emissions from maritime transport account for approximately 8% of all greenhouse gas emissions covered by the EU ETS.
- The need to purchase emission allowances will increase operational costs, which will initially be passed on to clients as an additional fee.
- In the RoRo and RoPax segments, a modal shift toward road and rail transport could occur.

*Table 3 - Overview of Key Design Features in the Revised EU ETS Directive (June 2023) (EP and EUCO, 2023a)*

Ship categories covered	Ships >5000 GT. Offshore ships specifically serving operational purposes such as oil exploration will be included from 2027. Including ships exceeding 400 GT will be considered following an investigation of its economic, environmental, and social impacts.
GHGs included	CO <sub>2</sub> included from 2024 and CH <sub>4</sub> and N <sub>2</sub> O emissions from 2026.
Geographical coverage	All intra-EU traffic, including port emissions, and 50% of the emissions from incoming and outgoing traffic.
Entities regulated	The shipowner responsible for surrendering emissions allowances

<sup>1</sup> 'Fit for 55' describes a set of measures and targets that the EU needs to implement to achieve a 55% reduction in greenhouse gas emissions by 2030 compared to the 1990 baseline. Launched in July 2021, 'Fit for 55' includes measures to reduce greenhouse gas emissions across various sectors, but this document will focus on proposals and directives relevant to the maritime sector. Specifically, these include FuelEU Maritime, the Energy Taxation Directive (ETD), the Renewable Energy Directive (RED), the Alternative Fuels Infrastructure Regulation (AFIR), and the EU Emissions Trading System (ETS).

Allocation of allowances	Via auction.
Use of revenues from allowance sales	Revenues transferred to member states' budgets and should be used mainly for climate-related purposes. The EU Innovation Fund should support investments to decarbonize the maritime transport sector
Time frame	The surrendering of allowances by shipping companies will be gradually increased with respect to verified emissions reported for 2024 (40%) and 2025 (70%) until full inclusion beginning in 2026.

Inclusion of the maritime sector in the EU ETS is expected to provide significant incentives for emissions reduction. In the short term, costs associated with the EU ETS will be passed on to transport users as additional fees. If these increased costs are not adequately addressed, emissions could spill over into less regulated sectors. Meanwhile, in the roll-on/roll-off (RoRo) and roll-on passenger (Ro Pax) segments, a modal shift toward road and rail transport could occur, given the direct competition and relative ease of switching to alternative transport modes.

In our case study analyzing the Ro Pax route between Prizna and Žigljen, which connects the island of Pag to the mainland, there is a paradox related to CO<sub>2</sub> emissions. Specifically, Pag is connected to the mainland by a bridge on the southern side of the island. However, the largest influx of vehicles and passengers comes from the northeast, and taking the ferry shortens the road journey by 150 km, saving 28 kg of CO<sub>2</sub> per car per one-way trip, or 56 kg CO<sub>2</sub> round-trip. Given that approximately 400,000 vehicles (1,000,000 passengers) are transported annually, this results in an estimated CO<sub>2</sub> reduction of 22,400 tons. If the Ro-Ro ferry annually consumes approximately 6,500 tons of diesel (for sailing, maneuvering, and port operations), emitting 17,030 tons of CO<sub>2</sub>, this effectively results in a carbon footprint saving of 5,370 tons of CO<sub>2</sub> per year.

### 3.3. Case Study Description

While various R&D studies have explored the feasibility of using different fuels (Hosseini & Butler, 2019), on zero-emission vessels, also examining batteries, various types of fuel cells (FCs), and hydrogen-based energy systems on vessels, this paper focuses on a vessel used for transporting vehicles and passengers over relatively short distances. Additionally, it emphasizes the unique application by studying the feasibility of installing different energy systems (also considering various types of FCs) and fuel types from economic, energy, and integration perspectives on the vessel.

The choice to focus on this type of vessel for the proposed retrofit project is driven by three reasons (Elkafas, Rivarolo, Barberis, & Massardo, 2023): (1) the fact that a short-sea RoPax vessel, given its travel profile, requires a limited propulsion system

capacity and fuel volume to be stored onboard, overcoming the main limitations associated with the large hydrogen tank that would need to be integrated; (2) the fact that this type of vessel, given its travel profile, follows a very frequent and precise schedule, enabling easy planning of refueling (further reducing the amount of fuel stored onboard); (3) the fact that this type of vessel operates in an environment where demonstrating FC technology efficiency on ferries could have a significant social impact in terms of public awareness.

The proposed case study involves one of the RoPax vessels operating on a short route connecting the island of Pag with the mainland. This type of vessel can be considered an entry point/showcase for clean propulsion solutions, as it does not require extensive onboard storage and has a high impact on passengers, especially during the tourist season, potentially increasing public awareness of clean maritime technologies. The route distance from Prizna to Žigljen is 4 nautical miles (8 km), corresponding to a travel time of approximately 00:14 hours. The number of daily departures depends on the season (10-12 trips during peak season, 5 in off-season).

*Table 4 - Characteristics of the case study RoPax CRES*

PARAMETER	UNIT	VALUE
Length between perpendiculars, Lpp	(m)	80
Length overall, Loa	(m)	87,6
Breadth	(m)	17,5
Depth	(m)	37
Draught	(mm)	2.400
Freeboard length	(m)	75,85
Freeboard (mm):	(mm)	1312
TMC 69 gross tonnage, GT	m <sup>3</sup>	2.474
TMC 69 net tonnage, NT	m <sup>3</sup>	781
Speed	kn	11,5
<b>Machinery</b>		
Diesel, four stroke, single acting	pcs	4
Total power output	kW	1.616
Propellers, fixed blade	pcs	4
Total power of generators	kW	3.444

The RoPax „Cres“ is powered by four fixed-pitch propellers (FPP) driven by four Volvo Penta 165A diesel engines, each with a maximum rated output power of 1,616 kW. The engine room contains four Volvo Pentas and two auxiliary generators (with rated outputs of 18 kW and 6 kW) for hospitality and service production. The

total maximum power during navigation (engine operation) is 3,444 kW. The vessel is designed to operate at a maximum speed of 11.5 knots, but the actual service speed (as reported through interviews with the local crew) for the studied journey and route is approximately 10.2 knots in navigation mode as a maximum. This service speed under normal weather conditions can be achieved using approximately 70% of the rated power of the installed engines (about 1,130 kW).

The operational profile of the RoPax „Cres“ includes various modes: passenger and vehicle boarding at port A (Prizna), maneuvering the ferry ½ nautical mile away from the terminal area (A-B), crossing the Velebit Channel (B-C), maneuvering to approach the Žigljen terminal (C-D), and unloading vehicles and passengers. The operational profile for a single journey is presented in detail in the following table and corresponding graph.

*Table 5 - Operational Profile of the A - D and D - A Journey*

	Board/ Unload	Maneuв.	Navig.	Maneuв.	Boarding/ Unloading	Maneuв.	Navig.	Maneuв.	Boarding/ Unloading	Σ
Time (h)	0:05	0:03	0:09	0:03	0:05	0:03	0:09	0:03	0:05	0,45
Fuel Consumption (l/h)	1	2	6,3	2	1	2	6,3	2	1	23,6

The operational profile of the RoPax „Cres“ for a single trip, departing from Prizna and ending at the port of Žigljen, is identical to the return journey from the port of Žigljen to the port of Prizna in terms of time and fuel consumption. Based on the limitations of available weight and volume on board, this study is designed for an energy system capable of performing 10 consecutive trips without refueling (or recharging, in the case of a fully electric battery system).

The maximum number of trips is deliberately taken during a peak tourist season (June to September). This aligns with the daily travel profile as shown in Figure 2; thus, ten one-way trips (OWT) can be considered a functional unit for assessing power and fuel capacity requirements. The study aims to investigate the feasibility of replacing conventional diesel engines with alternative clean energy systems based on FC and battery technologies.

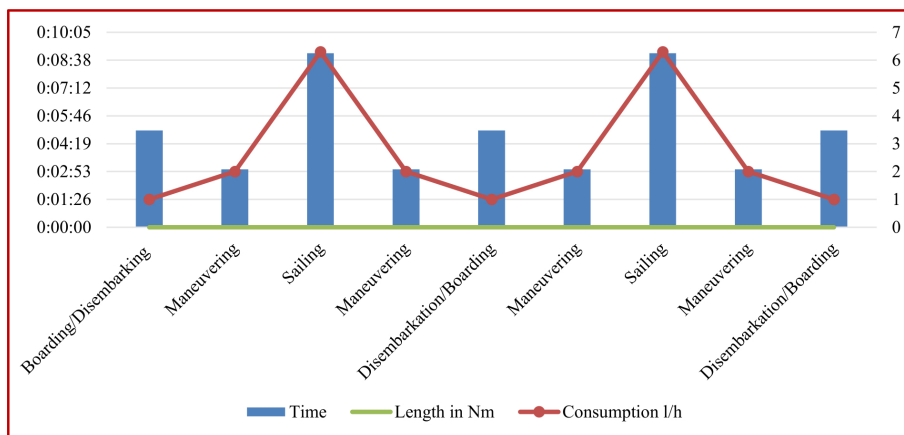


Figure 1 - Illustration of the Relationship Between Operational Time on a Round Trip and Fuel Consumption

The operational profile of the journey is visually represented in the following image.

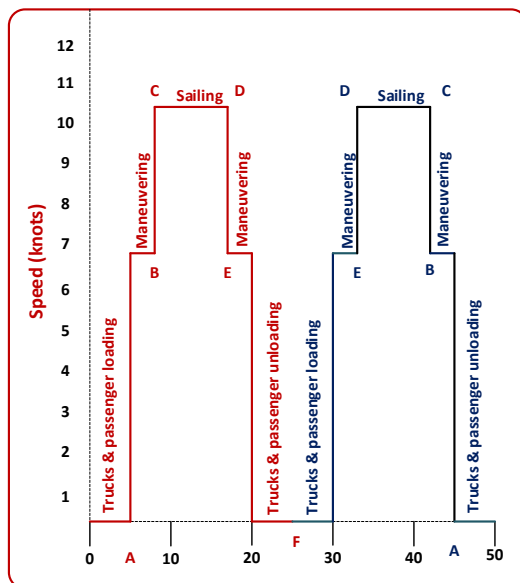


Figure 2 - Operational Profile of RoPax for a Single Round Trip

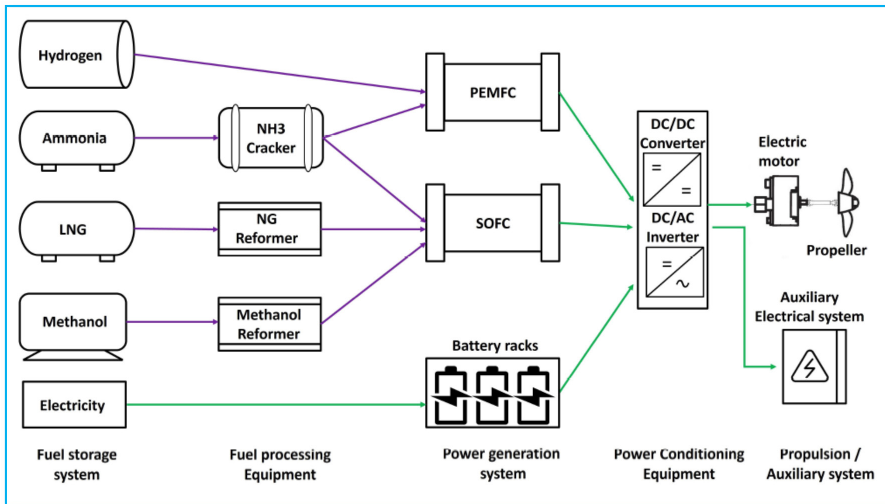


Figure 3 - Conceptual Diagram for Designing Clean Energy Systems

Source: (Elkafas, Rivarolo, Barberis, & Massardo, 2023)

As shown in Figure 3, there are five categories: fuel storage system, fuel processing equipment, power generation system, power conditioning equipment, and propulsion/auxiliary system. For the power generation system, three different technologies are considered—proton-exchange membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC), and battery system. For the onboard fuel storage system, the following fuels are evaluated: hydrogen, ammonia, LNG, and MeOH, along with the associated fuel processing equipment. The power conditioning equipment consists of DC/DC converters and DC/AC inverters, while the fuel processing equipment depends on the fuel type and includes ammonia crackers, natural gas reformers, and MeOH reformers. Regarding the propulsion system, an electric motor is selected to be present in all proposed cases to deliver the required power to the FPP (fixed-pitch propeller).

### 3.4. Relevant Scenarios

The most promising directions for establishing energy systems on RoPax vessels in short-sea shipping are: 1) fuel cell systems and 2) battery systems, and suitable scenarios are explored in this context.

#### 3.4.1. Fuel Cell System Scenario

The first step in defining system boundaries involves calculating the required power capacity for the propulsion and auxiliary systems using fuel cells (FC). This

determines the number of FC modules to be installed on the vessel, considering the typical capacity of commercial FC modules. It is assumed that the current power requirements for the propulsion and auxiliary systems (in the diesel ferry) remain constant and are applicable to the new clean energy system, except for the additional load associated with auxiliary devices when using the FC system, which is added through an additional factor.

This approach also allows for calculating fuel consumption, taking into account FC efficiency, fuel type, and additional fuel processing equipment. The FC efficiency ( $\eta_{FC}$ ) depends on the fuel cell technology and the required load. The amount of fuel also depends on the fuel type, which varies according to its lower heating value (LHV), expressed in kWh/kg. The required fuel mass for using the FC system (FM<sub>FC-f</sub>) to achieve the specified functional unit (10 OWTs) can be calculated using equation (5).

$$FM_{FC-f} = \sum_{J_{owt}=1}^{J_{owt}=10} \sum_{OM=s}^{OM} \frac{(1 + f_{se,f}) \cdot P_{OM,owt} \cdot T_{OM,owt}}{\eta_{FC-LHV_f}} \quad (5)$$

In this analysis, FM<sub>FC-f</sub> is expressed in kilograms, where  $f_{se,f}$  is an additional factor accounting for the equipment needed for extra fuel processing, while  $f$  denotes the type of fuel.  $P_{OM,owt}$  represents the average required power for each operational mode OM during a S specific journey, expressed in kilowatts (kW).  $J_{owt}$  is the number of OWT-s included in the calculation, and  $T_{OM,owt}$  represents the duration of each operational mode during the journey, expressed in hours.

If ammonia is used as a hydrogen storage medium onboard, additional fuel processing equipment must be considered, including a cracker and purifier for the catalytic decomposition and purification of residual ammonia to ensure pure hydrogen for the PEMFC system (Zhao, Liang, & Liang, 2022). The efficiency of auxiliary systems must be considered when calculating ammonia consumption.

When integrating fuel cells on vessels, an initial warm-up period is needed, particularly for SOFC technology. It is recommended to install a battery rack that provides the necessary energy for heating during the FC system startup. The function of the battery rack is to supply energy to heat the system to the operating temperature, after which the FC supplies the electric power needed for vessel propulsion. In the PEMFC system, the energy required for heating depends on the fuel used. Using ammonia as a hydrogen carrier requires more energy for heating than using pure hydrogen due to the operation of the cracker and purifier.

### 3.4.2. Full Battery System Scenario

The battery rack is a key component of the electrical energy system explored in this study, and its capacity must be sufficient to enable the vessel to complete the specified route. In this analysis, lithium-ion batteries are proposed due to their superior

characteristics compared to other types of batteries, including high energy capacity, reduced self-discharge rate, fast charging capability, and long lifespan.

To compensate for the gradual reduction in battery capacity due to slow degradation, the battery rack capacity must be increased by 20%, as capacity loss can reach up to 20% of the original capacity. Additionally, an extra 30% capacity (10% for safety and 20% for maintaining minimum capacity) should be added to ensure reliability. Due to these requirements, the total battery capacity (ECBT) must meet the vessel's energy needs for performing the specified function and increase by a total of 50%. The total capacity can be calculated using the formula shown in equation (6).

$$EC_{BT} = \sum_{J_{owl}=1}^{J_{owl}=10} \sum_{OM=s}^{OM} \cdot 1,5 \cdot P_{OM,owl} \cdot T_{OM,owl} \quad (6)$$

Since battery lifespan can also be expressed as the number of battery cycles, the batteries will be replaced multiple times based on the vessel's lifespan and the number of journeys per year.

### 3.5. Total Cost Assessment Method

Economic assessment of different power systems can be conducted by evaluating total costs, which encompass all expenses associated with the power system over the vessel's lifespan. In this approach, total costs are divided into three components: CapEx, OpEx, and VoyEx.

CapEx represents the investment and installation costs of the power system. OpEx includes maintenance, operational, and component replacement costs. VoyEx refers to the annual costs of fuel or electricity consumption needed for the vessel's operation. Based on these components, the total cost of the clean energy system can be calculated using the formula shown in equation (7).

$$TC_{cps} = CapEx_{cps} + \sum_{n=1}^{LT} OpEx_{cps,n} + \sum_{n=1}^{LT} VoyEx_{cps,n} \quad (7)$$

where  $TC_{cps}$  is the total cost of the clean power system (cps) over its lifetime, and  $n$  is the number of years in the vessel's lifespan (LT).

#### 3.5.1. Capital Expenditure (CapEx)

CapEx represents the total investment cost for the clean energy system. The proposed system includes five key categories: power generation system, fuel storage system, power conditioning equipment, fuel processing equipment, and electric motors.

The power generation system may consist of a PEMFC system or a battery rack. Fuel storage system costs are a significant part of CapEx, as the fuel for these systems differs from conventional marine fuels, which is particularly important in the context of replacing an existing power system, as in this study.

The costs of power conditioning equipment include the prices of DC/DC and DC/AC converters. The total CapEx for the proposed clean energy system can be calculated using the formula shown in equation (8).

$$CapEx_{cps} = CF_{ps} \cdot P_{ps} + CF_{fss} \cdot FC_{FC-f} + \left( \sum_{pce} CE_{pce} \cdot P_{ps} \right) + CF_{em} \cdot P_{ps} + \left( \sum_{oc} CF_{oc} \cdot P_{ps} \right) \quad (8)$$

In this analysis,  $P_{ps}$  represents the rated power of the proposed power system, measured in kW for the PEMFC or SOFC system and in kWh for the full battery system. Cost factors CF are used in equation (8), differing based on components:

- $CF_{ps}$  is the cost factor for the power system, expressed in EUR/kW or EUR/kWh.
- $CF_{fss}$  is the cost factor for the fuel storage system, expressed in EUR/kg of fuel.
- $CF_{pce}$  is the cost factor for power conditioning equipment, expressed in EUR/kW.
- $CF_{em}$  denotes the cost factor for electric motors, expressed in EUR/kW.
- $CF_{oc}$  represents the cost factor for other components, such as reformers and crackers, expressed in EUR/kW.

The following table shows cost factors for power system components and their main technical parameters.

*Table 6 - Investment Cost Factors and Technical Parameters for Power System Components*

Component	Cost Factor (CF)	Technical Parameter	Reference
PEMFC	1500 EUR/kW	$\eta_{peak} = 55\%$ , ZFC = 20.000 h	(SRIA, 2022)
SOFC	5000 EUR/kW	$\eta_{peak} = 60\%$ , ZFC = 20.000 h	(SRIA, 2022)
Battery	210 EUR/kWh	YBC = 5.000	(EMSA, 2020)
DC/DC converter	120 EUR/kW	$\eta = 98\%$ , LT = 25 years	(Kanchiralla et.al 2022)
Electric motor	250 EUR/kW	$\eta = 96\%$ , LT = 25 years	(DeVries, 2019)
Hydrogen tank	480 EUR/kgH <sub>2</sub>	LT = 25 years	(Belloti, 2022)
LNG reformer	370 EUR/kW	LT = 25 years	(Baldi, 2019)
MeOH reformer	475 EUR/kW	LT = 25 years	(Kanchiralla)
Ammonia cracker	250 EUR/kW	LT = 25 years	(Baldi, 2019)

Source: (Elkafas, Rivarolo, Barberis, & Massardo, 2023)

Cost factors for ammonia, methanol, and LNG storage tanks can be calculated, as explained by Rivarolo et al. (2021), using mathematical equations that link the required storage capacity to the storage tank price.

### 3.5.2. Operational Expenditure (OpEx)

For all power systems, an annual maintenance cost growth rate of 2% is assumed. Maintenance costs for battery-powered systems are estimated at 1% of their CapEx per year. Since batteries need to be replaced multiple times over the vessel's lifespan, replacement costs can be estimated based on the anticipated average price.

Similarly, operational costs for FC systems include maintenance and replacement costs. For PEMFC systems, an annual maintenance cost of 2% of their initial capital investment is assumed. A key factor in the OpEx of FC systems is the replacement cost, which depends on the FC system's lifespan and the expected number of replacements over the vessel's lifetime.

### 3.5.3. Voyage Expenditure (VoyEx)

In this case, VoyEx is calculated based on the annual energy consumption and the type of energy source. To estimate the annual VoyEx, it is necessary to calculate the total costs by multiplying the energy consumption (fuel or electricity) per trip with its price (expressed in EUR/kWh), and then adding these costs for all trips during the year.

## 4. Results and Discussion

The results assess the feasibility of replacing the conventional diesel power system on the RoPax vessel "Cres" using three alternative power system scenarios. The discussion is divided into three subsections: the first focuses on the results of the energy analysis based on the alternative power system scenarios, while the second and third subsections present the feasibility assessment results from economic and design perspectives respectively.

### 4.1. Energy Analysis Results

Energy analysis plays a crucial role, especially when replacing a conventional system with a clean system like the one proposed in this study, as the number of installed FC/battery modules depends on the required power/energy to achieve the specified functional unit. Additionally, energy assessment is essential for designing an adequate fuel storage system, particularly when using alternative fuels with different volumetric densities compared to conventional diesel. Based on the collected data on the ferry and its operational profile shown in Figure 2, the electrical energy and energy requirements for this case study are presented in the following table.

Table 7 - Electric power and energy requirements to perform a one-way trip

Operational Mode	Time (min)	Rated Power (kW)	Energy Consumption (kWh)
Passenger and Vehicle Boarding	5	282,5	19,4
Departure Maneuver	3	565	28,31
Navigation	9	1.130	170
Arrival Maneuver	3	565	28,31
Passenger and Vehicle Unloading	5	282,5	19,4
<b>Total</b>	<b>25</b>		<b>265,42</b>

According to the explanation by Elkafas et al. (2023), the efficiency of fuel cells (FC) varies depending on the rated power and load factor in each operational mode. In this case, the efficiency for PEMFC can range between 46.5% and 53.5%, while for the SOFC scenario it varies between 51.5% and 58.5%.

On the other hand, for the full battery system scenario, the energy capacity must be increased by 50% above the estimated energy requirements in each operational mode.

## 4.2 Economic Feasibility Assessment Results

The total cost assessment of alternative clean power systems is based on various cost categories, including capital expenditures (CapEx) for the power system. Additionally, it includes the total expected operational costs (OpEx) and voyage costs (VoyEx) over the vessel's lifespan, estimated at 20 years. VoyEx costs have the largest share of total costs for all PEMFC scenarios and the full battery system scenario, due to high prices of fuel or electricity.

Operational costs for the full battery system are similar to those of PEMFC systems but are lower compared to the OpEx of SOFC systems. The OpEx of the SOFC system remains constant regardless of the type of fuel used, as it depends on replacement and maintenance costs, which are not fuel-dependent.

## 4.3. Design Feasibility Assessment Results

This section examines the feasibility of replacing the conventional diesel power system on the „Cres“ ferry using three alternative power scenarios from a design perspective. In the retrofitting process, certain components will be removed, including four main diesel engines, two gearboxes, two auxiliary generators, and two diesel fuel tanks, with a total estimated mass of 30 tons and a volume of 50 m<sup>3</sup>.

According to the power and energy requirements analysis, the „Cres“ ferry needs 1,130 kW of power at maximum service speed, while achieving 10 OWTs in the full battery system scenario requires an energy capacity of 2,757 kWh.

In the PEMFC scenario with hydrogen as the fuel (the most feasible scenario), the required power for the „Cres“ can be achieved using six Ballard Fcwave modules (2024), providing a total rated power of up to 1,200 kW.

For the full battery system, according to specifications of Corvus battery racks (2024), the required energy capacity of 2,757 kWh can be provided by 22 battery packs (each pack containing 16 modules, with each module having a capacity of 8.3 kWh).

## 5. Conclusions

This paper analyzes the feasibility of replacing the conventional power system with alternative clean energy systems on one of the passenger ferries in a short-sea shipping fleet. The ferry was examined to assess the retrofit process for a “zero-emission” propulsion system. This type of vessel is considered suitable for testing the sustainability of innovative maritime technologies due to its low energy consumption, high public impact, and route, especially during the tourist season. The clean energy systems considered include fuel cell technologies and a fully battery-electric system, with PEMFC (low-temperature fuel cell) and SOFC (high-temperature fuel cell) technologies analyzed.

The hydrogen-based PEMFC system proved to be the most environmentally friendly, with a substantial reduction in CO<sub>2</sub> emissions over the vessel’s lifetime and savings of 60 EUR per ton of CO<sub>2</sub>, making this scenario a priority choice.

From a weight and volume perspective, the hydrogen-based PEMFC system is the best choice in this study, allowing for removal of the diesel system with 31.3% less weight and 34.6% less volume compared to the removed components.

The paper evaluates the feasibility of installing an alternative clean energy system instead of the diesel system from energy, design, and economic perspectives. The design assessment includes analyzing the system’s weight and size, focusing on defining components, while the economic sustainability of the power system is assessed using cost indicators.

Although the paper primarily focuses on a case study of the “Cres” ferry, the methodology for technical and economic assessment can also be applied to other passenger ferries on short routes to decarbonize maritime units. For larger vessels, especially from an economic perspective, it would be essential to consider savings through CO<sub>2</sub> tax exemptions (in the light of ETS implementation) and external effects, such as lower sanitary system costs due to reduced NO<sub>x</sub>, SO<sub>x</sub>, and PM emissions in urban areas.

The contribution of this paper includes a detailed analysis of a RoPax vessel through a real-world case, exploring various input parameters. An assessment of

environmental and economic aspects of using different fuels and carbon pricing is included. Each trade-off between different fuel scenarios and carbon pricing schemes will provide valuable information to shipowners and regulators.

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