Proceedings of the 15th International Marine Design Conference (IMDC-2024)
June 2-6, 2024
Amsterdam, the Netherlands

Functional analysis of speed, battery pack capacities and chargers of small electric ships - Adriatic Sea case study

Vedran Slapničar[1]*, Jerolim Andrić[2] and Smiljko Rudan[3]

ABSTRACT

Electric propulsion refers to propulsion using a combination of an electric motor and batteries. Electric motors powered by batteries represent a significant solution within the broader context of sustainability, energy efficiency, and technological advancement. As energy containers, batteries are characterized by low energy and power density and are currently not considered suitable for use on large displacement ships. Consumption of electric ships depends on numerous factors and the performance of the vessel's energy system requires great attention. The basic limitations are the ship's size and speed, the built-in capacity of the batteries, charging infrastructure, and sailing distance. These limitations are discussed and justified in two case studies in which the existing diesel-powered ships are replaced with electric ones.

KEY WORDS

functional analysis; electric ships; batteries; chargers; speed

INTRODUCTION

Today's challenging replacement of internal motor combustion with electric motors powered by batteries or other alternative energy sources includes many variables and we can say that it is very difficult to recommend the best solution. In principle, each case should be considered independently. In this paper, 9 shipping lines were analysed, namely 7 existing ones on which existing ships with diesel propulsion are already sailing, and 2 potentially new ones. For existing lines and potentially new lines, an analysis was made of which electric-powered ships could replace the existing ships. In this paper, batteries are treated as a potential energy source on board as an option that has already been applied. Considering the topicality of this issue, a relatively large number of papers have been published that consider the problem from various points of view but do not give a unique solution which is understandable. So, the literature review would take a quite lot of references without a serious sense of it. Here, we are referencing characteristic papers dealing with certain important topics. We can say that the sort of endless loop of solutions spins between the following topics, but not exclusively:

- Photovoltaic modules, solar energy
- Batteries
- Chargers
- Economics, cost
- Repowering, energy transition
- Operational profile, speed optimisation
- Coastal region, rivers, inland waters
- Lifecycle analysis

[1] Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, Croatia); ORCID: 0000-0002-3175-2542

[2] Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, Croatia); ORCID: 0000-0001-5968-5807

[3] Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, Croatia); ORCID: 0000-0002-5904-5938

* Corresponding Author: vedran.slapnicar@fsb.unizg.hr

Submitted: 23 February 2024, Revised: 27 April 2024, Accepted: 1 May 2024, Published: 7 May 2024

Conference paper, DOI: https://doi.org/10.59490/imdc.2024.782 e-ISSN: 3050-4864

The possibilities of isolated energy systems of islands by the usage of photovoltaic power systems for charging battery-powered electric ferries are discussed in (Frković et al, 2022). The paper (Kortsari et all, 2022) aims to present and explore the economic performance of a pure electric ferry, E-ferry. The E-ferry prototype is a viable commercial solution from a purely economic standpoint, according to the results of the economic examination. The E-ferry prototype, for example, has greater building expenses, but it has far lower operating costs overall, especially when it comes to fuel and energy resulting in a 5-8-year payback period. Comparably, even while battery systems have contributed significantly to the cost of the E-ferry, the ongoing decline in battery prices positions completely electric ships as a sustainable option. The auxiliary charging system is another significant factor in the E-ferry prototype's overall cost. To conclude, this is valid for the specific routes and belonging infrastructure. Evaluation of the possibility of using alternative fuels for small ferries based on several parameters, including technical readiness, regulations, GHG emission reduction, capital expenditure, and operational expense is elaborated in the paper (Laasma et all, 2022). When concentrating on the ferry business, it is crucial to take regional peculiarities and chances for lines into account. To attain carbon neutrality in the area, the paper's conclusion calls for more research to be conducted, including case studies of more specialized ecosystems with more obvious answers and possible courses of action. Considering the repowering option with battery-electric technology authors of the paper, (Mao et all, 2021), found out that passenger ferries up to 55 m that sail on legs up to 50 NM would replace 50% of fossil fuel use with electricity. But it must be considered that they had considered 10 MW chargers, which is still very doubtful in most countries.

We can agree, with the general conclusion given in (Pense & Akinoglu, 2020), that in the era of intelligent transportation systems, fully electric drive systems in the maritime industry may represent a significant step toward safer, more environmentally friendly, and more sustainable shipping globally, particularly when paired with solar energy or other renewable energy sources. In recent years, the most flexible approach to ship decarbonization may have been to build an entirely electric, battery-powered vessel. Battery-powered ships have a lower energy redundancy and a higher initial investment cost than conventional ships. Thus, it is essential to have an energy management plan that may reduce operating costs while ensuring the safety of energy use. The non-linear ship energy and speed optimization model describes energy usage under various sailing circumstances and speeds (Sun et al, 2022). Batteries and the safety of usage are another important issue (Trombetta et al, 2024). To guarantee ship efficiency and ensure high survivability and reliability, battery systems and their auxiliaries must be arranged. This could be done by complexly designed integrated power and energy systems that can link, track, and manage numerous onboard systems, including those for cooling, heating, detecting, alerting, and firefighting. The Filipino study (Vakili & Ölçer, 2023) also examines the environmental effects of battery-powered versus traditional diesel ferries, revealing that eco-friendliness pivots upon the nation's electricity mix. Battery-powered ships show promise for decarbonizing local waterways, provided there is a shift toward cleaner energy sources. The authors present a novel location problem called the electric riverboat charging station location problem, which is inspired by river operations with an electric vessel (Villa et al, 2020). This problem considers the necessary infrastructure for an electric vessel to be able to perform a round trip. The size of the electric vessel battery system and the placement of the solar-assisted charging stations are designed to keep expenses to a minimum. It incorporates both the charging function and the variation of solar radiation as a nonlinear behaviour function.

A case study (Wang et al, 2021) of a battery-powered fast catamaran ferry is employed, The various ship life phases and activities are taken into consideration by LCA and LCCA to create a life cycle emission inventory and calculate the associated costs. The findings show that when grid mix electricity from 2019 is used, the battery-powered system has life cycle greenhouse gas emissions decreased by approximately 30% and life cycle expenses lowered by 15% when compared to a conventional power system. Finally, it is necessary to properly plan the service network to offer high-quality transportation services. Thus, under service time constraints, the study (Wang et al, 2022) concurrently examines the positioning of charge stations, charging plans, route planning, ship schedule, and ship deployment. A literature review shows us the importance of carefully planning the sailing route of a ship powered by electric energy, speed, and consumption, as well as the necessary infrastructure for a certain ship to sail smoothly on a certain line. An insight into the conditions and limitations of the application of electrically powered ships was intended to be given in this work.

In the following sections, the elaboration of the work follows. Section 2 elaborates basic features of the ships' electrical eco-system and gives a comparison of features of the electric ships. For the selected lines, existing and new ones, the analysis of passenger ships is done in Section 3. The estimation of power and energy for the passenger ships of 45 m and 17 m together with the case studies is given in Section 4. A preliminary proposal of technical specifications for the new battery-powered solar-electric passenger ships to be deployed on selected lines is presented in Section 5. Finally, at the end, the Conclusion is given.

BASIC FEATURES OF THE SHIPS' ELECTRICAL ECO-SYSTEM

Electric drive refers to a system using a combination of an electric motor and a battery pack. Batteries, as energy storage, are characterized by low energy and power density and are currently not considered suitable for use on larger ships. In recent years, significant progress has been made in the development of batteries, especially when it comes to charging speed and reducing the memory effect of charging. Lithium batteries' current energy storage capacity is about 300 Wh/kg (Thunder Said Energy, 2024). In most batteries the critical metal is lithium and the world's lithium reserves are estimated at 23 million tons, most of which are stored in Chile (Statista, 2024). An alternative is to use magnesium, which is much more abundant, but it is still in the research phase. Table 1 depicts the advantages and disadvantages of using electric energy.

Table 1: The advantages and disadvantages of using electric energy

Advantages	Disadvantages
• Complete absence of greenhouse gas emissions during vessel operation. • Batteries seem suitable for powering smaller ships in the short to medium term. • In combination with other types of drives, it is possible to realize a hybrid drive, applicable for propelling smaller and medium-sized ships.	• The size and mass of the batteries currently limit the application of the batteries mostly to smaller-sized ships and very short distances. • Battery-powered ship's propulsion needs to be further developed, and even with significant progress, it is likely to expect the installation of such propulsion only on smaller-sized ships. • The battery pack must be replaced and disposed of at the end of its working life, which is determined by the total number of charging and discharging cycles.

Consumption of electric battery-powered ships depends on numerous factors and the performance of the vessel's energy system requires great attention. The basic limitations are the built-in capacity of the batteries, the permissible percentage of battery discharge (DOD-Depth of discharge), the value of the upper limit of the battery charge, the speed and frequency of charging, the sailing route, weather conditions, and the way the vessel is operated. If we consider only navigation, energy consumption depends on a series of manoeuvres of acceleration, deceleration, docking, manoeuvring in the port, and an adaptation of the driving style to sea conditions, environmental temperature, and other conditions. Energy consumption needs to be compensated by charging battery systems, whereby chargers differ in terms of installed power and charging speed, ease of use, charging losses, etc. The construction of chargers is regularly associated with significant infrastructure costs and sometimes administrative and technical difficulties. It can be concluded that the electric battery-powered ship is part of an energy ecosystem in which each component of the system needs to be adjusted optimally for the system.

Designing an energy ecosystem for electric battery-powered ferries requires knowing the answers to the following related questions:

1. What are the prices of energy from the local utility?
2. Are there special prices for off-peak energy consumption or permitted service interruption?
3. What will be the infrastructure needed for shore charging?
4. Is there a large-capacity power supply on-site at the terminal?
5. Is there a possibility of a power supply at both ends or all parts of the route?
6. Who pays/finances the charging infrastructure?
7. What emergencies are allowed?
8. What happens if the energy grid is temporarily unavailable?
9. How "green" is the energy that is purchased/used?
10. What is the durability of batteries and what about their disposal?
11. What new technologies are in the pipeline that can improve performance and reduce costs?
12. How far is the location for the ship overhaul?
13. Does the vessel have to react to emergencies such as rescue actions?

The main part of the energy ecosystem, questions 1-9, should be addressed by governmental administrative activities and by building the infrastructure. Questions 10-11 depend on market development and certainly, the designer will choose the best batteries on the market when designing the battery system that satisfies safety issues and has valid certificates. Question 12 is the question for the ship operator, it depends on the specific area but also it is a part of the infrastructure because if we don't have repair places nearby, then it will be almost impossible to deploy any ships on certain lines. Question 13 depends on some specific needs that could be prescribed by the classification rules and/or national statutory rules.

Energy supply and battery systems for maritime applications

The supply of energy to ships that use batteries as the main or auxiliary energy source is only possible with the existence of a dedicated infrastructure. To be able to electrify ships on certain lines, it is necessary to provide infrastructure for fast/adequate battery charging at least at one of the endpoints of these lines. Therefore, energy supply must be ensured for each case within the framework of long-term transportation network planning.

One of the problems that should be stated is that the energy supply infrastructure, specifically intended for the supply of new solar-electric battery-powered ships on the selected existing and potentially new lines, currently doesn't exist, so the problem of deploying the new ships is even greater. Generally, the battery systems for maritime applications can be considered by very high reliability, large system capacity, modularity, and high safety in use. System certification is performed by classification societies and one of the most important tests includes a detailed heat transfer simulation. The risk of excessive heat transfer is reduced by the battery management system (BMS), integrated heat dissipation, and fire protection system. Although classification societies allow the use of new types of batteries with great caution, unlike lead batteries, due to the risk of ignition.

Comparison of features of electric ships

Table 2 shows the part of the basic features of 10 electric ships that are publicly available. Some data were slightly different due to the different data sources, and some data were not even publicly available. Also, some inconsistencies in the data can be seen, although they are given on the manufacturer's website. Given the fact that only the data of installed engine power is available, and not the data of the required engine power for the corresponding service speed, it can be concluded that the power of the installed engines on some lines is quite higher than necessary, i.e. the larger power reserve was taken. Data in the table are presented in the wide range of ship length, 24.5 m -144 m, and number of passengers, 132 – 1250. It is also visible from the table that the sailing time is mostly less than 30 min., except in two cases.

Table 2: Presentation of basic features of electric ships

Name of the ship	**Ampere 2015** (Ship Technology, 2015)	**Aurora and Tycho Brahe 1991-2017** (Wikipedia, 2023)	**Ellen 2019** (Wikipedia, 2024)	**Ika Rera 2022** (Danfos, 2022)	**Amherst Islander II 2019** (Damen, 2024)	**Wolfe Islander IV 2019** (Damen, 2024)	**Basto Electric 2020** (Ferry Shipping News, 2020)	**M/S Sjövägen 2014** (Wikipedia, 2024)	**Legacy of The Fjords 2020** (Baird Maritime, 2020)	**BB Green 24 2020** (Jackson, 2021)
Hull type*	CAT	MONO	MONO	CAT	MONO	MONO	MONO	MONO	CAT	MONO
Length, m	80	111	59.4	19	71.7	99.3	144	24.50	42	24.8
Number of passengers /cars	360/120	1250/240	198/31	132	300/42	399/75	600/200	150	400	147
Sailing time-one direction, approx.. min.	20	20	100	30	20	20	30	50	60	30
Speed, kn	10.00	14.50	12.10	20	12	12	12.80	10	20	35
Engines. kW	900	6000	1500	650	2080	2080	2250	320	900	660
Batteries, kWh	1000	4160	4300	540	1940	4500	4000	500	1800	500
Mass of batteries, t	10.0	57.0	56.0	5.5	25.0	58.5	52.0	5.0	23.4	5.0

*CAT - Catamaran; MONO - Monohull

ANALYSIS OF PASSENGER SHIPS ON SELECTED LINES – EXISTING/NEW ONES

As stated in the introduction 9 lines listed in Table 3 were analysed, 7 existing ones and 2 potentially new ones. The first 4 are served by high-speed catamarans (Lines Nos. 1-4), with service speeds between 14.8 - 21.03 kn, while Lines Nos. 5-7 are served by slow-speed monohull ships, with service speeds between 10-11 kn. Based on the previous work it was decided to investigate the possibility of placing slow-speed catamarans on potentially new lines, Line Nos. 8-9, with a speed of 10 kn. Catamaran was chosen for potentially 2 new lines due to the size of the ferry ports at the destination points and because it has a relatively large available area for passenger accommodation about the ship's length. The paper aimed to analyse the feasibility of replacing the existing diesel-powered ships with fully electric ships using batteries as an energy source, but also, to deploy the same kind of ships on the new lines. In Table 3 the 2 values per shipping line are presented, namely, distance per trip and consumption per trip. Distance per trip represents the total distance that a ship navigates in one direction. Consumption per trip depends on the required engine power for the service speed, hotel consumption, maximum voyage time, and efficiency coefficient (from the battery to the propeller), taken here as 0.92. Required engine power is obtained by in-house software based on the Holtrop-Mennen method (Holtrop & Mennen, 1978),

Table 3: List of analysed shipping lines

	Line No.	Line name	Distance per trip NM	Consumption per trip kWh
Exisitng lines	1	9601-Split-Rogač-Stomorska-Sutivan-Milna	33.00	1706
	2	9602-Split-Milna-Hvar-Vis	29.80	2036
	3	9406-Zadar-Zaglav-Zadar	22.20	675
	4	9604-Split-Hvar-Vela Luka-Ubli	61.13	4870
	5	310-Mali Lošinj-Srakane Vele-Unije-Susak	36.83	1201
	6	505-Šibenik-Zlarin-Prvić Luka-Prvić Šepurine-Vodice	20.18	658
	7	807-Dubrovnik-Koločep-Lopud-Šipan	22.79	1068
New lines	8	Split-Postira-Omiš	16.80	229
	9	Gaženica-Zadar-Borik	8.40	115

All these lines with their schedules and existing ship data (Row Nos. 1-9) were preliminarily analysed as follows (Table 4):

- Considering the navigation route and the schedule, the real service speed was calculated since these values were not available (Row No. 10). The available data were the maximum speed and total engine power.
- Using the in-house computer program the required power for the service speed was estimated (Row No. 11).
- Considering the navigation route and schedule the navigation distance without charging is determined (Row No. 12)
- Considering the battery depth of discharge (80% DOD + 10% reserve), the losses in the system, the ship's speed, the required power for service speed, available charging time and assumed charger power, the capacity of the batteries was calculated (Row No. 13).
- The fuel oil mass was obtained from the available ship's documentation (Row No. 19).
- The mass of the required batteries was calculated conservatively by multiplying the capacity of the batteries with the coefficient 13 kg/kWh (Row No. 24).
- The ratio of the mass of the required batteries and the fuel oil mass obtained from the existing ship documentation was calculated. The criterion of the feasibility indicators for replacing energy sources from fossil fuels with batteries is set (Row Nos. 26 and 28).
- A Feasibility Indicator 1 shown in Figure 1 was introduced as the ratio of the required mass of batteries and the fuel oil mass of existing ships, mBATT/mFUEL (Row No. 26) . According to this indicator, the existing ship on the existing line is feasible if it is less than or equal to 1. The feasible lines are Line Nos 5,6,7, and 9, while Line No. 8 could be probably feasible with some additional adjustments.
- Another indicator, Feasibility Indicator 2 shown in Figure 2, is the relation between the energy source and deadweight. Namely, fuel oil mass and deadweight, mFUEL/mDWT (Row No. 27), and required mass of batteries and deadweight, mBATT/mDWT (Row No. 28). This indicator should be less than 35%.

Considering the Feasibility Indicator 1, the high-speed ships lines 9602, 9601, 9604, and 9406 are not feasible since the values of this indicator range from 3.0 to 7.1. To conclude, the lines on which it would be possible to replace energy sources from fossil fuels with batteries must generally have lower speeds, larger charging time frames and shorter sailing distances. The sailing schedule must be harmonized to enable the daily charging of the batteries also, otherwise, the battery pack capacity needs to be too large. In any case, each line should be analysed individually with the existing parameters and limitations, and if the lines are not feasible, it is necessary to design a new ship considering the realistic requirements for passenger capacity, required speed, and sailing schedule to enable consumption of electric energy as low as possible. Last, but not the least, any changes to the existing sailing schedule and passenger capacities should be coordinated with the needs of the users and the local community. This is because they are already accustomed to a certain sailing schedule with existing passenger ships powered by diesel engines, so it is necessary to explain why changes would be necessary for the ships powered by batteries.

Table 4: Preliminary calculation of capacity of the battery pack for the passenger ships on selected lines

			Line No.	1	2	3	4	5	6	7	8	9
			Line name	9601	9602	9406	9604	310	505	807	Split-Postira-Omiš	Gaženica-Zadar-Borik
			Hull type	CAT	CAT	CAT	CAT	MONO	MONO	MONO	CAT	CAT
Row No.		Unit	Data/calculation									
1		m	L - length	37.37	36.85	24.5	36.00	45.00	45.00	45.00	17.00	17.00
2		m	B - breadth	11.00	11.00	9.00	10.10	10.00	10.00	10.00	7.00	7.00
3		m	T - draft	1.19	1.20	1.28	1.79	2.50	2.50	2.50	0.97	0.97
4		m	b - demihull width	2.83	2.83	2.32	2.60	-	-	-	2.10	2.10
5		-	CB - block coefficient	0.480	0.480	0.480	0.480	0.607	0.607	0.607	0.486	0.486
6		t/m3	ro - sea density	1.025	1.025	1.025	1.025	1.025	1.025	1.025	1.025	1.025
7		t	LS - Lightship mass	85.6	84.8	49.2	113.89	612.9	612.9	612.9	22.05	22.05
8		t	DWT - Deadweight	38.7	38.3	22.2	51.3	80.1	80.1	80.1	12.5	12.5
9		t	Displacement	124.3	123.1	71.5	165.0	702.0	702.0	702.0	34.5	34.5
10		čv	v - service speed	18.4	21.0	14.8	21.0	10.0	10.0	11.0	10.0	10.0
11		kW	Pb - Required power for service speed	850.3	1297.0	389.2	1514.0	275.1	275.1	449.2	110.5	110.5
12		NM	d - navigation distance without charging	33.00	59.60	44.40	61.13	36.83	20.18	22.79	16.80	8.40
13		kWh	ENG - Battery capacity	2900	6800	2300	8150	2100	2100	2150	430	250
14		kWh	maxENG - maximum consumption between charging	1706	4072	1350	4870	1201	658	1068	229	115
15		h	t - maximum voyage time	1.79	2.83	3.00	2.92	3.68	2.02	2.07	1.68	0.84
16		kW	Maximum charger power on the route	1250	500	400	975	335	665	1000	350	450
17		g/kWh	SFOC - specific fuel oil consumption	170	150	185	170	170	170	170	170	170
18	**=8/9**	-	etaDWT = DWT/Displacement	31.1%	31.1%	31.1%	31.1%	11.4%	11.4%	11.4%	36.1%	36.1%
19		t	mFUELdoc (fuel mass obtained from ship documentation)				16.68	32.1	32.1	32.1		
20	**=19/8**		etaFUEL = mFUELdoc/DWT				0.325	0.401	0.401	0.401		
21	**=14*17/10^6**	t	equiFUEL=maxENG*SFOC/1000000 (Equivalent fuel consumption per voyage)	0.29	0.61	0.25	0.83	0.20	0.11	0.18	0.04	0.02
22	**=20*8**	t	mFUEL = etaFUEL*DWT (Assumed fuel mass based on the mFUELdoc)	12.57	12.45	7.22	16.68	32.10	32.10	32.10	4.05	4.05
23	**=22/21**	-	nVOYAGE = mFUEL/equiFUEL (The number of voyages a ship can make using diesel fuel without refuelling)	43.3	20.4	28.9	20.1	157.2	287.0	176.8	104.0	207.2
24	**=13*(13 kg)**	t	mBATT = ENG*13 kg (Battery mass)	37.70	88.40	29.90	105.95	27.30	27.30	27.95	5.59	3.25
25	**=22-24**	t	deltaDWT=mFUEL-mBATT ("-" means that the ship lacks deadweight)	-25.13	-75.95	-22.68	-89.27	4.80	4.80	4.15	-1.54	0.80
26	**=24/22**	-	mBATT /mFUEL (Relation of battery mass and fuel mass)	**3.0**	**7.1**	**4.1**	**6.4**	**0.9**	**0.9**	**0.9**	**1.4**	**0.8**
27	**=22/8**	-	mFUEL/DWT (Relation of fuel mass and deadweight)	32.5%	32.5%	32.5%	32.5%	40.1%	40.1%	40.1%	32.5%	32.5%
28	**=24/8**	-	mBATT/DWT (Relation of battery mass and deadweight)	97.5%	230.8%	134.5%	206.5%	34.1%	34.1%	34.9%	44.9%	26.1%

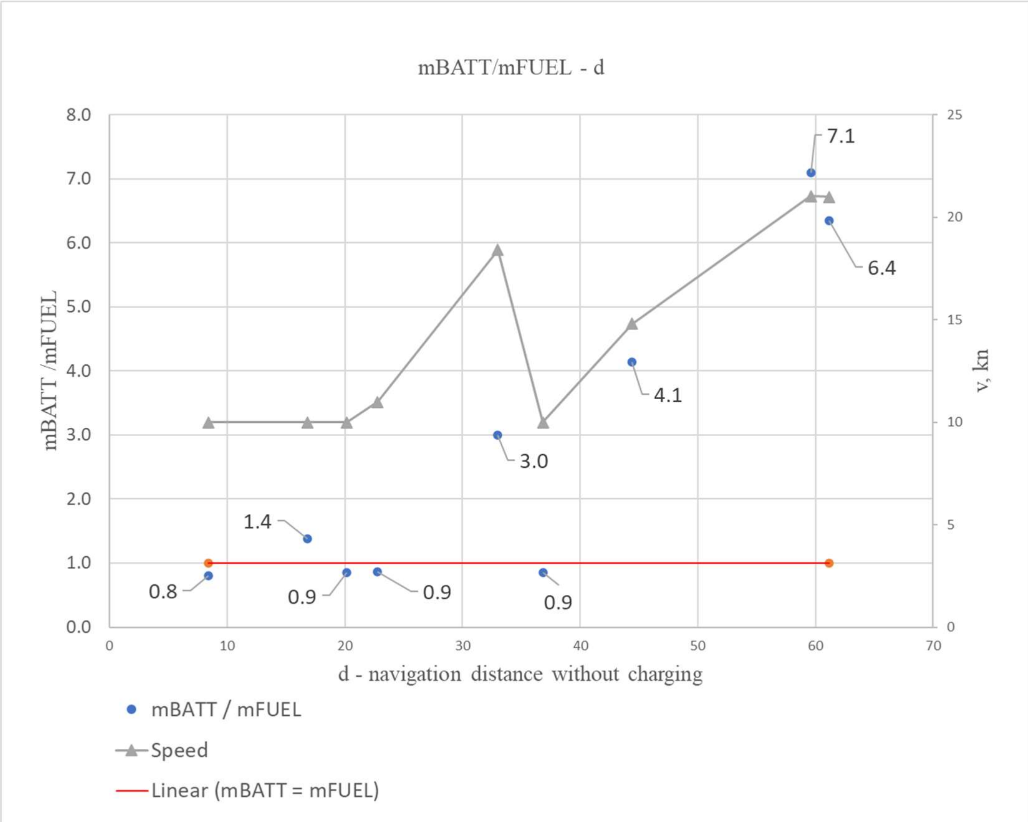

Figure 1: Feasibility Indicator 1 - relation of required mass of batteries and fuel oil mass

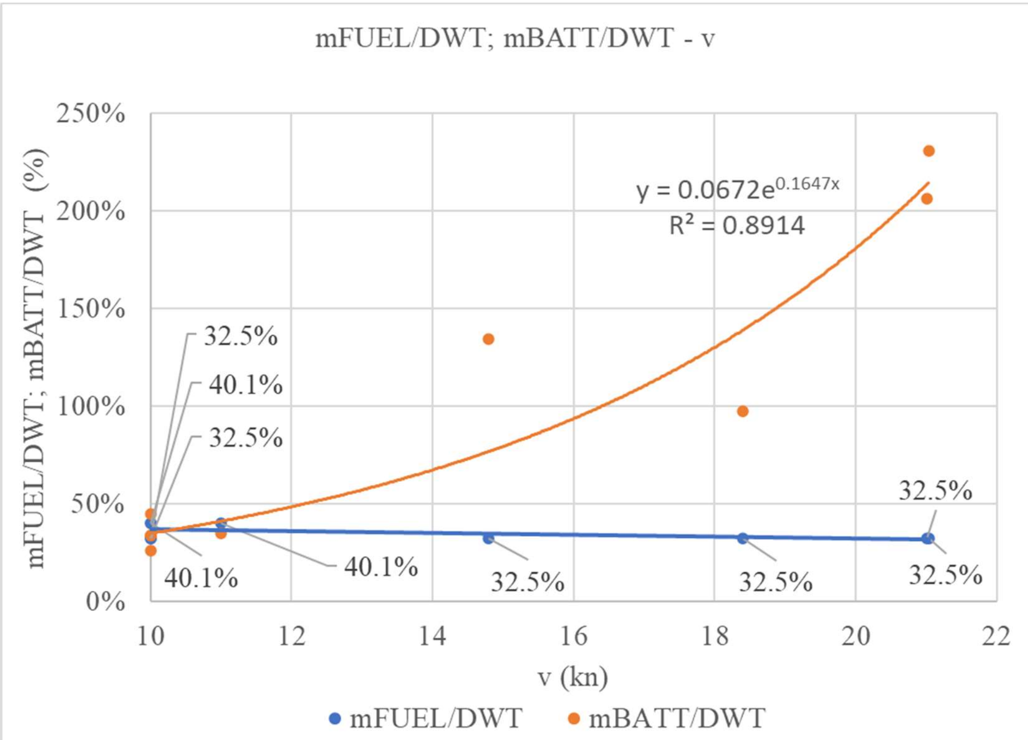

Figure 2: Feasibility Indicator 2 – the relationship between the mass of the energy source and deadweight

ESTIMATION OF POWER AND ENERGY - CASE STUDIES

Estimation of power and energy for a 45 m passenger ship

For a passenger ship with a length of 45 m for lines 310, 505, and 807, Table 4, Line nos. 5-7, the required engine power was estimated (Holtrop & Mennen, 1978) as shown in Figure 3. For the speed of 10 kn, the required engine power is 275,08 kW, while for the speed of 11 kn, the value is 449.19 kW. Considering that these values represent 90% of MCR (Maximum continuous rating), the built-in engines should have a total power of 300 kW, or 2 x 150 kW for the speed of 10 kn, and 500 kW, or 2 x 250 kW for the speed of 11 kn. The bow thruster power is assumed to the 20% of the main engine power, or 2 x 15 kW for the speed of 10 kn and 2 x 50 kW for the speed of 11 kn. Together with the required engine power, the required battery pack capacity as well as the required charger power were calculated for the original sailing schedules. To avoid unnecessarily high battery pack capacity as well as high charger power, an analysis of the schedule was performed. This analysis showed that the small changes in the schedule would enable daily charging of the batteries, and consequently lower battery pack capacities and charger powers. Regarding the gain of solar energy, the average daily value in kWh per 1 kW of installed photovoltaic module, for the location of Mali Losinj, is 3.21 kWh (PVGIS, 2024). The number of 350 W photovoltaic modules, considering the assumed allowable free superstructure roof area of 360.00 m^2 amounts to 180, and they provide 201.95 kWh, which is 9.4% of the battery pack capacity. Considering the electric motor voltage of 705.6 V, the battery pack has 2150.67 kWh with a total weight of 27.95 t. The battery pack consists of 42 modules and 10 strings, where each module has 32 battery cells of capacity 38.1 Ah and voltage 4.2 V.

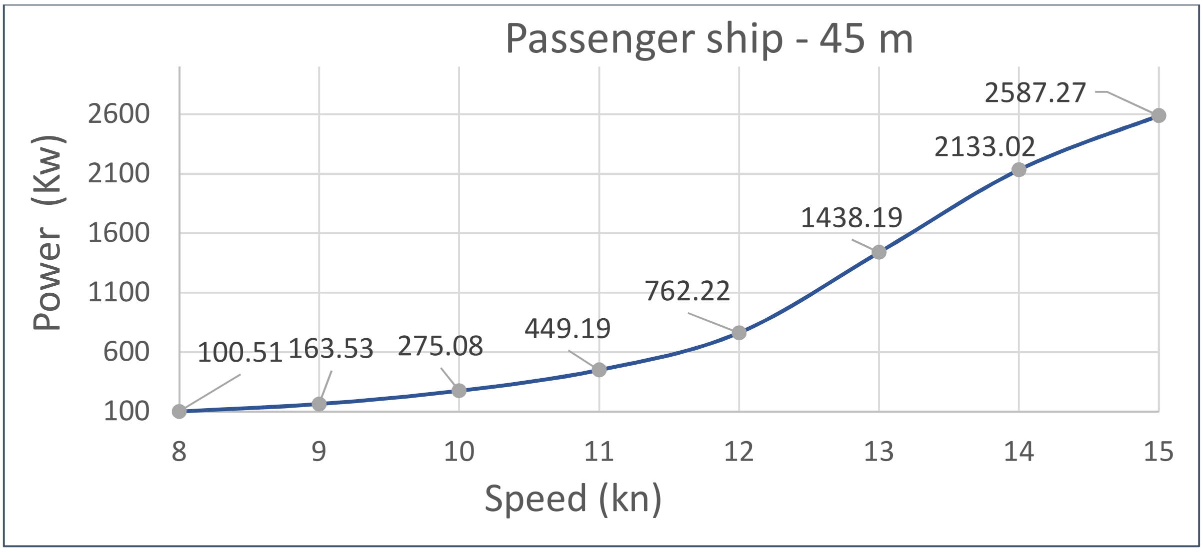

Figure 3: Power-speed diagram for a 45 m passenger ship

Hotel consumption of a 45 m passenger ship (air conditioning, vessel devices, lighting) is assumed during navigation 25 kW, and by the night charging 10 kW.

Analysis: Case study 1 - State line no. 807

"Case study 1" gives a detailed analysis of the state line no. 807 as an example of a 45 m passenger ship. The original sailing schedule for the high season is shown in Figure 4, and the navigation distance is 22.79 NM. Although the service speed for line 807 is 11 kn, the required battery pack capacities and chargers were calculated for 3 speeds (Table 5), so the battery pack capacity ranges from 3450 kWh to 6800 kWh and daily charger in Dubrovnik from 1000 kW to 3000 kW.

HIGH SEASON

01.07. - 28.08.

MONDAY - SATURDAY				SUNDAY AND HOLIDAY				PORTS	MONDAY - SATURDAY				SUNDAY AND HOLIDAY			
I	II	III	IV	I	II	III	IV		I	II	III	IV	I	II	III	IV
06:00	11:55	15:20	18:30	07:30	10:20	17:00	19:35	SUĐURAĐ	11:15	15:15	17:45	21:15	10:15	13:00	19:30	22:15
06:15	12:10	*	18:45	07:45	10:35	–	19:50	LOPUD	11:00	15:00	17:30	21:00	10:00	12:45	19:15	22:00
06:20	12:15		18:50	07:50	10:40		19:55		10:55	14:55	17:25	20:55	09:55	12:40	19:10	21:55
06:40	12:35	15:45	19:10	08:10	11:00	17:25	20:15	KOLOČEP	10:35	14:35	17:05	20:35	09:35	12:20	18:50	21:35
06:45	12:40	15:50	19:15	08:15	11:05	17:30	20:20		10:30	14:30	17:00	20:30	09:30	12:15	18:45	21:30
07:15	13:10	16:20	19:45	08:45	11:35	18:00	20:50	DUBROVNIK	10:00	14:00	16:30	20:00	09:00	11:45	18:15	21:00

Figure 4: Original schedule for the state line no. 807

Table 5: Required capacity of battery packs and chargers for speeds of 10, 11 and 12 knots for the state line no. 807 - original schedule

V=12 kn	No schedule change
Sudurad: min charging power (kW)	**650 kW**
Dubrovnik: min charging power (kW)	**3000 kW**
Input: nominal battery capacity (kWh)	**6800 kWh**

V=11 kn	No schedule change
Sudurad: min charging power (kW)	**430 kW**
Dubrovnik: min charging power (kW)	**1850 kW**
Input: nominal battery capacity (kWh)	**4500 kWh**

V=10 kn	No schedule change
Sudurađ: min charging power (kW)	**330 kW**
Dubrovnik: min charging power (kW)	**1000 kW**
Input: nominal battery capacity (kWh)	**3450 kWh**

It is necessary to provide two power chargers, a higher capacity charger in Dubrovnik for daytime charging and a lower capacity charger in Sudurad for overnight charging. Considering the very high required battery pack capacities and the chargers' power (Table 5), a slight modification of the original schedule is necessary. With a slightly changed schedule, the required battery pack capacities and chargers' power have been significantly reduced compared to the obtained for the original schedule (Table 6). This gives us an overview of the possible combinations for the speed options 10, 11, and 12 kn.

Table 6: Possible options for the battery pack capacities and chargers for speeds of 10, 11, and 12 knots for the state line 807 - slightly changed schedule

V=12 kn

Sudurad: min charging power (kW)	260	280	315	345	375	400	430
Dubrovnik: min charging power (kW)	1630	1570	1480	1410	1330	1275	1200
Input: nominal battery capacity (kWh)	2800	3000	3300	3600	3900	4200	4500

V=11 kn

Sudurad: min charging power (kW)	180	210	245	270	290	320	345
Dubrovnik: min charging power (kW)	1075	975	900	825	775	715	640
Input: nominal battery capacity (kWh)	1900	2200	2500	2800	3000	3300	3600

V=10 kn

Sudurad: min charging power (kW)	125	160	185	215	240	270
Dubrovnik: min charging power (kW)	750	660	590	525	450	375
Input: nominal battery capacity (kWh)	1300	1600	1900	2200	2500	2800

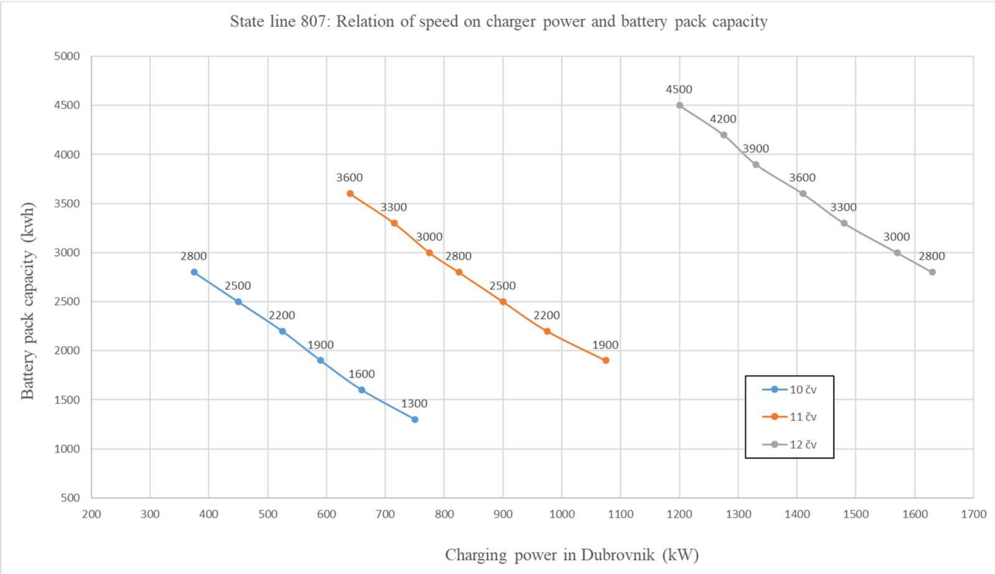

Figure 5: State line 807: Effect of speed on charger power and battery capacity

Table 7: State line 807: slightly changed schedule to enable more time for charging

Trip	Original harbour time, min	New proposed harbour time, min	Charging=harbour time-10, min	Harbour time, hours	Battery trip start, kWh	Consumption per voyage, kWh	Battery trip ends, kwh	Available battery charger capacity, kWh
1	165	105	95	1.58	1935	534	1401	1326
2	50	80	70	1.17	1935	1068	867	977
3	10	80	70	1.17	1844	1068	776	977
4	15	50	40	0.67	1753	1068	685	558
					1243	534	709	

Daily charging in the Dubrovnik, 1000 kW charger

Overnight charging in Suđurađ, 7 hours including 10 kW for hotel consumption, 200 kW charger

Estimation of power and energy for a 17 m passenger ship

For a passenger ship with a length of 17 m for lines Split-Postira-Omis and Gazenica-Zadar-Borik, Table 4, Lines Nos. 8 and 9, the required engine power was estimated (Holtrop & Mennen, 1978). For the speed of 10 kn, the required engine power is 110.49 kW as shown in Figure 6. Taking into account that this value represents 90% of MCR, the built-in engines should have a total power of 130 kW, or 2 x 65 kW. The bow thruster power is assumed to the 20% of the main engine power, or 2 x 12 kW. The required engine power, battery pack capacity, and charger power are calculated considering the following parameters:

- the assumed sailing schedule on the line Gazenica-Zadar-Borik is 11 departures per day, but the charging is done only in Gazenica port in 20 min. after each round voyage. Assumed nominal charger capacity is 450 kW and battery pack capacity 250 kWh.
- assumed sailing schedule on the line Split-Postira-Omis, 2 departures per day, charging is done in both ports after each voyage with the assumed nominal charger capacity of 350 kW and battery pack capacity of 430 kWh.

Since these two lines are supposed to be completely new, considering the estimated engine power and hotel consumption, the required battery pack capacity as well as the required charger power the schedule proposal was given by the authors to avoid unnecessarily higher capacities. Regarding the gain of solar energy, the average daily value in kWh per 1 kW of installed photovoltaic module, for the location of Mali Losinj, is 3.21 kWh (PVGIS, 2024). The number of 350 W photovoltaic modules, considering the assumed allowable free superstructure roof area of 95.20 m^2 amounts to 48, and they provide 53.85 kWh, which is 12.5% to 21.54% of the battery capacity, depending on the line.

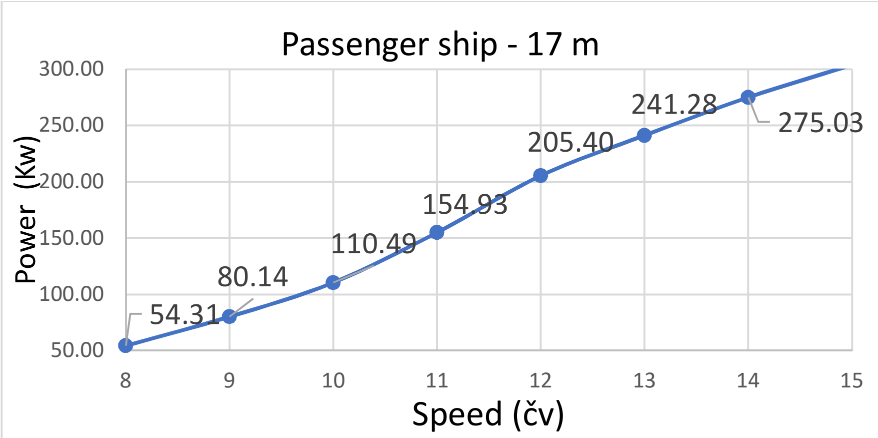

Figure 6: Power-speed diagram for a 17 m passenger ship

Hotel consumption of a 17 m passenger ship (air conditioning, vessel devices, lighting) is assumed during navigation 15 kW, and the night charging 5 kW.

Analysis: Case Study 2 - Line Gaženica – Zadar – Borik

"Case study 2" gives a detailed analysis of the state line Gazenica-Zadar-Borik as an example of a 17 m passenger ship. The assumed schedule for the line Gazenica-Zadar-Borik and back takes 70 min. for a round trip including the necessary time for boarding and disembarking the passengers, with 30 min. for a break in Gazenica port, of which 20 min. is for charging (Table 8). For the speed of 10 kn the possible options of the combinations for the battery pack capacities and chargers are given in Table 9.

Table 8 Voyage and charging description for line Gaženica – Zadar – Borik

Harbour time, min	Trip	Charging= Harbour time-10, min	Harbour time, hours	Battery trip start, kWh	Consumption per voyage, kWh	Battery trip ends, kWh	Available battery charger capacity, kWh
30	1	20	0.33	225	115	110	125
30	2	20	0.33	225	115	110	125
30	3	20	0.33	225	115	110	125
30	4	20	0.33	225	115	110	125
30	5	20	0.33	225	115	110	125
30	6	20	0.33	225	115	110	125
30	7	20	0.33	225	115	110	125
30	8	20	0.33	225	115	110	125
30	9	20	0.33	225	115	110	125
30	10	20	0.33	225	115	110	125
30	11	20	0.33	225	115	110	

Daily and overnight charging in Gazenica, 450 kW charger

Table 9: Possible options for the battery pack capacities and chargers for the speed of 10 kn for the line Gaženica – Zadar – Borik

V=10 kn

Gazenica: min charging power (kW)	425	405	390	365	450
Nominal battery capacity (kWh)	200	250	300	400	250

The consequence of the proposed schedule and charger option is that the batteries will be charged 12 times per day, so they will be replaced approximately within 3 years.

PRELIMINARY PROPOSAL OF TECHNICAL SPECIFICATIONS FOR NEW SOLAR-ELECTRIC BATTERY-POWERED PASSENGER SHIPS ON SELECTED LINES

After the detailed analysis of all lines, in terms of rationalizing design and construction costs, it is proposed that the two types of fully electric battery-powered passenger ships could replace existing passenger ships on selected lines (Table 3)

- **Ship I** – monohull, length up to 45 m, for the service on existing lines 310, 505 and 807.
- **Ship II** – catamaran, length up to 17 m, for the service on new lines Split-Postira-Omis -Omiš and Gazenica-Zadar-Borik.

When proposing the preliminary dimensions of the new ships, the following aspects were considered:

- The technical specifications were chosen as an envelope of requirements for lines for which the same type of vessel is proposed.
- The proposed passenger capacity results from an analysis of the existing ships and shipping lines, which showed that the maximum capacity of the existing ships is sufficient to cover long-term needs on the selected lines.
- The speed of the ships, 10 to 11 kn, is specified in such a way that fits the schedule and as low as possible lower battery pack capacities and chargers.
- For lines 310, 505, and 807, the option for loaded cargo is 25 t, which can be breakbulk /pallet/container loaded by crane, together with the 3 medium-sized supply vehicles and 5 passenger cars loaded by a stern ramp.
- The proposed approximate dimensions of the larger ship, length up to 45 m, will be in line with the existing ships that currently operate on lines 310, 505, and 807. The passenger capacity for all lines is not the same and consequently, the length should not be the same, but since line 310 (Line No. 5, Table 3 and Table 4) is an open-sea line exposed to severe weather conditions that has by far the largest number of cancelled voyages, it is assumed that the same size ship should serve this line to ensure a reduction in the number of cancelled voyages.
- The proposed dimensions of smaller-sized ships consider the limitations of the potential berths at the ports of destination.

Table 10 provides a preliminary proposal for the technical specifications of new passenger ships on the selected lines.

Table 10: Preliminary proposal of technical specifications of new passenger ships on selected lines

	Ship I		**Ship II**	
	310, 505	**807**	**Gazenica-Zadar-Borik**	**Split-Postira-Omis**
Type of vessel	Pasenger ship		Pasenger ship	
Classification	HRB★50A1 IWS SD★M1 AUT3		HRB★50A1 IWS SD★M1 AUT3	
Class-passenger vessel	Class C-Rules for statutory certification		Class C-Rules for statutory certification	
Navigation area	national navigation 5/6		national navigation 6	national navigation 6
Length L [m]	up to 45 m		up to 17 m	
Width B [m]	Monohull, about 10 m		Catamaran, up to 7 m	
Draft T [m]	up to 2.5 m*		up to 1 m*	

Height H [m]	up to 4.2 m		up to 2.0 m	
Minimum speed, kn	10	11	10	10
Drive	Twin-screw, separate control systems		Twin-screw, separate control systems	
Type of propulsion –	electric		electric	
Passenger capacity	max 390 passengers		max 100 passengers	
Passengers open deck	140		-	
Passengers closed space	250		max. 100	
Cargo capacity	25 t		deck area 3 m2	
Crane capacity	-		-	
Number of crew	9		3	
Construction material	hull/superstructure: steel/aluminium		hull and superstructure: steel/aluminium alloy/	
Special requirements	Bow thruster, energy shore connection		Bow thruster, energy shore connection	
Flag	Croatia		Croatia	
Type of lines	Open sea	Open sea	Coastal	Open sea

*Note: regarding the maximum permissible draft, when finalizing the project, it is necessary to consider in detail the max. the depth of the pier according to the latest data.

CONCLUSION

Nine shipping lines were examined in this paper, 2 possibly new lines and 7 existing lines that are currently served by ships using diesel propulsion. An analysis was conducted to determine which electric-powered ships could replace the current ships on both existing and possibly new lines. Batteries are discussed in this paper as a potential onboard energy source that has already been used on certain lines and is a reasonably simple alternative to implement. In terms of the rationalization of design and construction costs, as previously stated, it is proposed to build two types of passenger ships, a 45 m Ship I and a 17 m Ship II, which could be deployed on selected lines with solar-electric-battery propulsion. The final dimensions and all technical characteristics of the ships will be defined by the initial design and technical descriptions, considering additional technical requirements and the actual depth condition at the intended piers. Some remarks must be stressed:

- The introduction of solar-electric battery-powered ships requires a deep analysis of the minimum necessary speed, for each line independently, to keep the energy consumption as low as possible.
- It is also necessary to harmonize the schedule to enable the daily charging of the batteries.
- For some existing lines, such as line 807 (shown as Case Study 1), the analysis showed that with a slightly changed schedule, the required battery pack capacity and charger power can be significantly reduced compared to the original schedule.
- Proposed changes to the sailing schedule should be harmonized with the needs of the users.
- The contribution of energy that can be obtained from photovoltaic modules installed on the superstructure roof area, ranges from 9.4% to 21.5%, depending on the particular line.
- The feasibility indicators are defined, as Feasibility Indicator 1 and Feasibility Indicator 2, and they must be within certain limits, i.e. under 1 and 35% respectively.

We see that electric energy for the propulsion of ships that use batteries as a potential energy source on board is not largely used and has not taken off as much as we might expect, in fact, its application, for now, is just on mostly very specific lines. The reason for this is the lack of infrastructure, the relatively small capacity of batteries and their large mass compared to diesel propulsion systems, engine rooms and supplies. Also, the cost of the batteries, as well as the problem of recycling batteries after a certain number of charging cycles is a real problem. In summary, the lines that may potentially replace energy sources from fossil fuel with batteries need to have slower speeds, longer charging times, shorter sailing distances, and with the sailing schedule carefully adjusted. In future work, it is planned to analyse the application of electric energy to larger ships that would have a hybrid drive, diesel-electric-battery, where the energy obtained from the batteries would be for ship departure and arrival, as well as during the ship's stay at the berth. The benefit of such a system would be the reduction of exhaust gases in the port as well as less noise.

CONTRIBUTION STATEMENT

Vedran Slapnicar: Conceptualization; data curation, methodology; writing – original draft.
Jerolim Andric: review and editing.
Smiljko Rudan : review and editing.

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