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Original scientific paper

Decarbonizing the Bay of Kotor: Preliminary Electrification Concept of a Ferry[*]

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Abstract: International Maritime Organization (IMO) and regional authorities have been gradually introducing decarbonization policies and regulations. Shipping sector's primary response remains the reduction of the cruising speed. Other solutions can include hull optimization, application of energy saving devices, alternative fuels. Alternative fuels are still under the development and could significantly reduce emissions, through the application of batteries, hydrogen, ammonia, etc. However, domestic voyages by ferries have not been exposed to the regulations' scrutiny. Nevertheless, in the regions such as the Bay of Kotor (Montenegro), protected by UNESCO, maritime transport is expected to follow environmental policies. In order to encourage the decarbonization of such regions, this paper offers a preliminary concept solution of an electric ferry for the Bay of Kotor with reduced onboard emissions. The concept is based on available data on the most energy demanding ferry in Bay of Kotor that has operated for the past decade. The ferry follows the short route suitable for the application of electric drive. Analysis of an operational profile and the ferry concept design parameters are presented, as well as the advantages and disadvantages of electric ferry proposal.

Keywords: Electric ferry, Bay of Kotor decarbonization, Energy efficiency, IMO, Decarbonization.

1. Introduction

After decades of climate change debates, Paris Agreement [1] united an international effort on defining the decarbonization goals, set to allow global temperature to rise by 2^0C or 1.5^0C, compared to the second half of the 19th century. Greenhouse gas (GHG) emissions were labelled as responsible for the climate change. Thus, countries have vowed to peak their GHG emissions as soon as possible. Following the Paris Agreement, the Intergovernmental

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Panel on Climate Change (IPCC), published reports on decarbonization pathways. Most recent IPCC report from 2022 [2] stated that, in order to reach 1.5^{0}C rise, global GHG emissions must peak until 2025 while much larger scale transition to renewable energy should be achieved.

In total anthropogenic GHG emissions, international shipping contributed by 2.89% in 2018 [3], while being responsible for over 80% of the international trade in goods by volume [4]. The share is expected to grow if nothing is done and other industries continue their energy transition; taking into account the annual increase of deadweight fleet by around 3% in 2021 [4]. Therefore, International Maritime Organization (IMO) has started delivering energy efficiency requirements to push the shipping sector towards decarbonization. IMO GHG requirements for new [5] and existing ships [6] have been introduced, namely: energy efficiency design index (EEDI), energy efficiency existing ship index (EEXI), carbon intensity indicator (CII), etc. Those regulations apply to most of the deadweight fleet participating in international voyages. More on energy efficiency of typical cargo ships built in the past two decades can be found in [7, 8].

Nevertheless, domestic voyages are excluded from the international maritime regulations and are governed by the national and local authorities. Such ships are not scrutinized for emitting harmful emissions. This is especially the case for areas protected as the natural and culture-historical regions by UNESCO (United Nations Educational, Scientific and Cultural Organization), i.e., World Heritage Sites. One of those sites is the city of Kotor and the part of the Bay of Kotor (Montenegro) [9]. The Bay of Kotor is experiencing an increase in maritime traffic, primarily from cruise ships, yachts, boats, and ferries. Cruise ships emission impact on health of habitants in coastal towns is thoroughly reviewed in [10], while the effect of multiple cruise ships in port is investigated in [11]. Furthermore, cruise ships emissions are assessed for the Bay of Kotor and city of Dubrovnik [12, 13]. Port emissions due to yachting, boating and other small-scale ships are still not systematically explored in areas similar to the Bay of Kotor. Nonetheless, their impact on environment is studied in [14, 15]. Finally, ferry transport air emissions are examined in range of operations worldwide, see [16, 17]. Particularly with regards to the Bay of Kotor, ferry transport air pollution is quantified in [18]. To conclude, the literature acknowledges the rise of air pollution due to increased traffic from ships burning traditional fossil fuels, in areas such as the Bay of Kotor or similar.

Considering the goal for the reduction of air pollution in protected areas, the aim of this paper is to propose the start of the decarbonization of the Bay of Kotor. The first step is set to be the decarbonization of the ferry transport.

2. Ferry concept electrification

The electrification design is based on the regularly used route for ferries over the decades, connecting the sides of the Bay of Kotor in Verige strait, between the ports of Kamenari and Lepetani, see Figure 1. Their operation provides less road and traffic congestion compared to the detour alternative around the bay, which frequently lasts more than an hour.

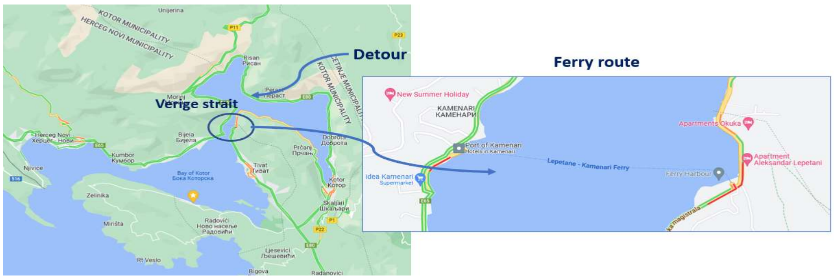

Fig. 1 – *Ferry route (reconstructed from google maps).*

The objective of the paper is to propose a preliminary design solution for a ferry with significantly lower onboard emissions than the existing diesel fuel ferry operating on the same route. The concept's aim is to provide a potential for route decarbonization while also relieving two inhabited ports of harmful air pollution. This can be achieved by modifying the existing ferry prototype design by replacing the diesel engine system with an electric drive with batteries. The selection of the electric concept is chosen for the preliminary design analysis due to short route profile.

2.1. Prototype

The prototype ferry ship “M/T Grbalj” is the largest and most energy demanding ship in fleet of ferries operating on a designated route for the past 10 years, see Table 1 and Figure 2.

Table 1 – *Prototype particulars* [19].

Type	RoPax (Ro-Ro double ended) steel monohull
Built	2009
Length overall (including ramps)	59.75 m
Breadth x draught	16 x 2.35 m
Deadweight	149 DWT (Note 1)
Gross tonnage	597 GT
Engines	2 x 447 kW, 1800 rpm
Speed	9 kn
Capacity	49 vehicles
Route distance	Around 900 m

Note 1. DWT for summer load line, according to data from [20, 21].

Summer is the most congested part of the year in which the ferry is working up to almost 24 hours a day, according to ship operator claims.

Fig. 2 – *The prototype at berth at the port of Lepetani.*

2.2 Operational profile and analysis

In order to select the batteries, exact operation profile must be determined based on real-time measurements performed during the summer season congestion. However, authors of this paper did not have those measurements. Nonetheless, the actual stages of the ferry operation follow trapezoidal curve. Therefore, for the purpose of the analysis, operational profile is reconstructed according to the following:

1. The prototype operation profile stages are identified based on available measurement data provided by the comparable ferry from the paper [22], given the assumption that most of the frequent and short ferry operations have the similar stages, namely: embarking, ramp lift, departure, cruising, arrival, berthing, ramp down, disembarking.

2. Authors of this paper performed real-time measurements on the prototype during series of crossings to determine average time of each of the stage in operation.

3. Former captain of the prototype ship provided data on average power used for each of the stage, namely: 80% of the main engines power is used for cruising, 30% of the generators power is used as a hotel power while embarking and disembarking, 70% of the main engines power is used when the load is increased after departure, 70% of the main engines power is used after reduction of the speed after the cruising stage.

There are two main sources of energy on-board: two main engines and two generators. Furthermore, total of three groups of consumers are using onboard produced energy: propulsion system (uses main engines power), auxiliary systems (use generators power) and hotel systems (use generators power). At each stage of the operation, at least one source is running. Therefore, based on official ship operator data [19] and data given by the former captain, the main power outputs are estimated and shown in Table 2. Moreover, taking into account the real-time measurements performed on-board of the prototype, adopted operational profile stages from [22] and insights from the former captain, data for the operational profile of the prototype are reconstructed and shown in Figure 3 and Table 3. The diagram is produced assuming linear model built upon averaged values in operation. The operation profile is shown as a dependency between the power during the single operation (start of embarking until end of disembarking) and duration (time). Base power is a hotel power and is constantly running to facilitate minimum required needs of the ship. Maximum power is achieved while cruising at 9 kn for 5 min. The total time needed for single (one) voyage is 12 min.

Table 2 – *Power estimations.*

Type of power	Methodology	Power
Main engines total power	$P_{tot} = MCR = 2 \text{ x } 447$ kW	$P_{tot} = MCR = 894$ kW
Two generators total power	(Note 1)	$P_{Gen} = 200$ kW
Main engines power for cruising at 9 kn	$0.80 \cdot P_{tot}$ (Note 2)	$P_{ME} = 715.2$ kW
Auxiliary systems and constant hotel loads	$P_{AE} = P_{Aux} + P_{Hot} = 0.866 \cdot \mathrm{GT}^{0.732}$ (Note 3)	$P_{AE} = 93.2$ kW
Constant hotel load	$P_{Hot} = 0.30 \cdot P_{Gen}$ (Note 1)	$P_{Hot} = 60$ kW
Auxiliary system load	$P_{Aux} = P_{AE} - P_{Hot}$	$P_{Aux} = 33.2$ kW

Note 1. Based on averaged output of the generators of the similar ferries operating in Mediterranean, according to the statistical analysis performed in [23].

Note 2. According to data provided by the former captain on average power used for the operation.

Note 3. According to IMO MEPC formula for auxiliary system and constant hotel load from [24].

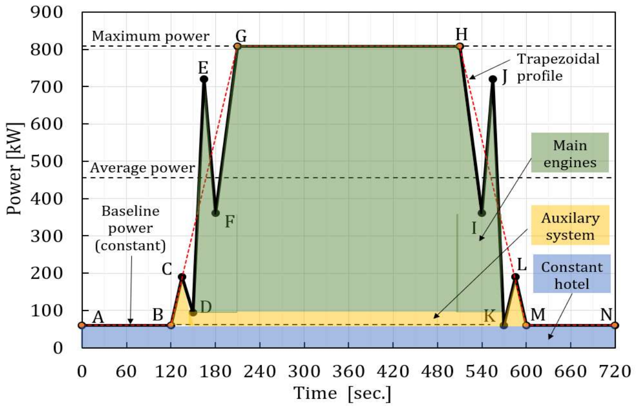

Fig. 3 – *Adopted operation profile.*

Table 3 – *Reconstruction of the data for operational profile.*

Stage	Comments	Methodology for power estimation	Estimated power
A-B (Embarking – 2 min.)	Constant hotel load is assumed as 30% of the total power of two generators	$P_{A\text{-}B} = P_{Hot} = 0.30 \cdot P_{Gen}$	$P_{A\text{-}B}$ = 60 kW
B-C (Ramp lift, phase 1 - 15 sec.)	From constant hotel load (B) to almost maximum load (95%) of two generators (C)	$P_B = P_{Hot} = 0.30 \cdot P_{Gen}$ $P_C = 0.95 \cdot P_{Gen}$	$P_B = P_{Hot}$ = 60 kW P_C =190 kW
C-D (Ramp lift, phase 2 - 15 sec.)	Ramp is lifted, but the power does not decrease to the hotel load because other systems start to power up for departure. Thus, power drop occurs at around half of the previous one.	$P_C = 0.95 \cdot P_{Gen}$ $P_D = P_C/2$	P_C =190 kW P_D = 95 kW
D-E (Departure, phase 1 – 15 sec.)	Power increases until additional 70% of the MCR is used.	$P_D = P_C/2$ $P_E = 0.70 \cdot MCR + P_D$	P_D = 95 kW P_E = 720.8 kW
E-F (Departure, phase 2 – 15 sec.)	Ship overcomes the resistance and thus, a short power drop occurs (F) before increasing to the maximum load (G).	$P_E = 0.70 \cdot MCR + P_D$ $P_F = 0.50 \cdot P_E$	P_E = 720.8 kW P_F = 360.4 kW
F-G (Departure, phase 3 – 30 sec.)	Power is increased until maximum power is reached for cruising at 9 kn (main engines + auxiliary systems + constant hotel load).	$P_F = 0.50 \cdot P_E$ $P_G = P_{ME} + P_{AE}$	P_F = 360.4 kW P_G = 808.4 kW
G-H (Cruising at 9 kn – 5 min.)	Ship uses maximum power: main engines + auxiliary systems + constant hotel.	$P_{G\text{-}H} = P_{ME} + P_{AE}$	$P_{G\text{-}H}$ = 808.4 kW
H-I (Arrival, phase 1 – 30 sec.)	Ship reduces the power to the half of the PE to prepare for approach.	$P_H = P_G = P_{ME} + P_{AE}$ $P_I = 0.50 \cdot P_E$	P_H = 808.4 kW P_I = 360.4 kW
I-J (Arrival, phase 2 – 15 sec.)	Power is increased for maneuvering.	$P_I = 0.50 \cdot P_E$ $P_J = 2 \cdot P_I$	P_I = 360.4 kW P_J = 720.8 kW
J-K (Berthing – 15 sec.)	Power is decreased for berthing by using just constant hotel load.	$P_J = 2 \cdot P_I$ $P_K = P_{Hot}$	P_J = 720.8 kW P_K = 60 kW
K-L Ramp down, phase 1 – 15 sec.)	Power is increased to almost maximum load (95%) of two generators.	$P_K = P_{Hot}$ $P_L = 0.95 \cdot P_{Gen}$	P_K = 60 kW P_L = 190 kW
L-M Ramp down, phase 2 – 15 sec.)	Power drops to constant hotel load.	$P_L = 0.95 \cdot P_{Gen}$ $P_M = P_{Hot} = 0.30 \cdot P_{Gen}$	P_L = 190 kW P_M = 60 kW
M-N (Disembarking – 2 min.)	The same as A-B.	$P_{M\text{-}N} = P_{Hot} = 0.30 \cdot P_{Gen}$	$P_{M\text{-}N}$ = 60 kW

Total energy and energy used by each of the consumers is calculated as an integral of the power (P)-time (t) function:

$$\int_A^N P dt = 91.1 \text{ kWh} \tag{1}$$

from Figure 3 and Table 4. *A* and *N* stand for the start (embarking) and the end (disembarking) of the single voyage profile, respectively, according to Table 3.

Table 4 – *Energy consumption per voyage and per hour.*

Consumers	Energy consumption [kWh]	
	12 min.	1 hour
Main engines	73.9	369.3
Auxiliary systems	5.2	26.2
Hotel	12.0	60
Total	91.1	455.5

3. Preliminary design

In first step of the preliminary design, capacity of batteries was adopted based on:

- the operational profile (Figure 3) and,
- the assumption that the displacement of the ship cannot be changed significantly.

3.1 Weights

The weight of the batteries represents the main obstacle, especially in achieving the prototype's unaffected displacement. Modifications include prototype's two main engines, two generators and fuel tanks, having in total 22.842 t available to be replaced by the batteries (Table 5). Authors of this paper did not have data on fuel tanks capacities so they were estimated based on assumptions that: daily fuel oil tanks (2 x 2 m^3) can provide daily operation of 18 hours in duration, main fuel oil tanks (2 x 8 m^3) can provide 72 hours of operation, specific fuel consumption of the installed main engines is 111 l/h according to manufacturer's data [25]. Diesel oil density is 837 kg/m^3, which delivers the consumption toward the 93 kg/h. Total weight of two generators is also taken from the manufacturer's data [26].

Table 5 – *Estimations of prototype weights.*

Item	Weights
Two main engines	4502 kg
Two generators	1600 kg
Two main fuel tanks	13392 kg
Two daily fuel tanks	3348 kg
Total	22842 kg

For the purpose of the preliminary analysis, it is assumed that ship's center of gravity remains almost unchanged, implying that new systems (electric, steering and propulsion) have approximately the same total weight as the old ones. As a result, the total weight of the batteries that can be installed onboard is 22.842 t, which is the same as the weight removed from the ship. This mass is a part of the lightweight mass of the ship. Moreover, additional analyses are carried out. For prolonged operation, batteries might be heavier than the removed weight, so the additional weight of the batteries surpassing 22.842 t will be taken into account on behalf the actual deadweight (DWT). Hence, in order to achieve increased time of operation with "overweight" batteries, ship's capacity might be reduced.

3.2 Electrical system selection

Onshore infrastructure for charging is not available at the site. Local power grid is not supporting the large power output chargers, although they are available as a technology. Considering that voltage of the charger directs the maximum power, it is supposed that a potential onshore charger would not have voltage greater than 1100 VDC. This would increase time to facilitate charging of batteries, so that the continuous ferry operation would not be possible. Therefore, an alternative solution is proposed. In conventional electric ship, batteries are placed in the hull (in-hull battery pack, i.e., IHBP), which is also the case here. Additionally, batteries will be placed on deck, in a movable container on a trailer. Movable container battery pack (MCBP) is suitable for sites with no developed power grid, because it can be charged onshore while the ship is in operation. During vehicle embarking and disembarking, the ship can dispose used batteries while loading up onshore charged ones. Therefore, an outline of the electrical system is proposed in Figure 4.

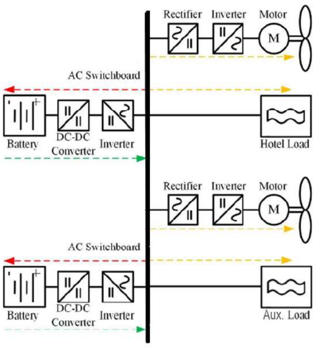

Fig. 4 – *An outline of an electrical system.*

The conversion of the power system considers adding two new components, DC-DC converter and inverter, to facilitate existing AC arrangement. Coefficients of efficiency are adopted based on recommendations given in [27], based on data for the ship all-electric driven powertrain and they are: battery efficiency η_b = 0.95, DC-DC efficiency η_{dc} = 0.989, converter efficiency η_r = 0.97, inverter efficiency η_i = 0.97, electric motor efficiency η_m = 0.965. P_{ME1} and P_{ME2} represent the powers of two main engines (P_{ME} is their total output), P_{Aux} is auxiliary engine power and P_{Hot} is a hotel load, see also Table 2. According to Figure 4, the following relation for the battery capacity (P_b) can be derived:

$$P_b = \frac{\frac{P_{ME1}}{\eta_r\eta_i\eta_m} + \frac{P_{ME2}}{\eta_r\eta_i\eta_m} + P_{Aux} + P_{Hot}}{\eta_b\eta_{dc}\eta_i} = \frac{\frac{P_{ME}}{\eta_r\eta_i\eta_m} + P_{Aux} + P_{Hot}}{\eta_b\eta_{dc}\eta_i} \quad (2)$$

As a result, ferry energy consumption is shown in Table 6.

Table 6 – *Ferry consumption.*

Time	P_b [kWh]
Single voyage (12 min)	108.2
1 hour	540.8

The main objective for the selection of batteries is that they must be class approved for the use in maritime sector. Moreover, considered are battery design recommendations from [28]. Finally, an available battery pack product is selected, see Table 7 and [29]. Selection of batteries are carried out based on manufacturer's recommendation that the depth of discharge should not be more than 80%.

Table 7 – *Battery module.*

Item	Xalt energy: Module XMP 98P (single module)
Energy	9.77 kWh
Dimensions	0.753 x 0.303 x 0.282 m
Weight	76.5 kg
Voltage (max.)	88.8 VDC

4. Operation

Besides fixed IHBP, ship is intended to use four MCBP. Thus, based on operational profile (Figure 3 and Table 4), battery packs were chosen, as shown in Table 8. IHBP consists of 12 modules in series and 144 in parallel circuit, while MCBP includes the 20 ft container that carry 12 modules in series and 240 in parallel circuit. In total, they deliver 3752 kWh, corresponding to 26 single voyages or constant 5 h and 12 min of operation. This will reduce spacing for two vehicles, or approximately 5-6 vehicles in terms of DWT (standard vehicle weight is assumed to be around 2 tons).

Table 8 – *Selected battery combination.*

	IHBP	MCBP
No. of modules in series circuit	12	12
No. of modules in parallel circuit	144	240
Circuit voltage	12 x 88.8 VDC = 1066 VDC	
Total energy	144 x 9.77 kWh = 1407 kWh	240 x 9.77 kWh = 2345 kWh
Total mass	11.93 t	21.62 t
Number of voyages achieved	10	16
Charging time (Note 1)	4 h 38 min	7 h 24 min
DOD (Note 2)	77%	74%
Time available for ship operations	2 h	3 h 12 min
Total time	5 h 12 min (26 voyages)	
Weight changes (Note 3)	+10.71 t (deadweight reduction, i.e., lightweight increase, corresponds to 5-6 removed vehicles)	

Note 1. Chargers are adopted with following specifics: 1100 VDC, 220 A, 242 kW.

Note 2. Depth of discharge, not to be more than 80%.

Note 3. According to the usual weight of cars of 1600-2200 kg. In addition, see Table 5.

If only one charger is considered to exist, for instance in port of Kamenari, the ship has to unload used and load new battery pack in the same port. Single MCBP is always used onboard while others are charging onshore. IHBP and MCBP consumptions are combined in order to keep the operation as prolonged as possible. IHBP is charged at the end of the day and operation.

Energy consumption of the electric ferry is divided into sequences so that the same trends are repeated every 18 voyages, see Figure 5. When MCBP is used, its energy decreases, whilst IHBP energy remains constant and unused. During the nineth voyage, IHBP is used and its energy decreases, whilst MCBP is constant and unused. The total available battery energy of the ship is steadily reducing as the number voyages rise. The in-service separate energy consumptions of MCBP and IHBP energy consumptions are illustrated in Figure 6, with respect to state of charge (SOC) and depth of discharge (DOD). MCBP timeframe is given for the period between the point of embarking onboard to the point of being fully charged in port. The MCBP line has steeper descent of energy consumption compared to the IHBP, meaning that the latter has better influence on the life of the battery of the IHBP. The ship is assumed to use one charged container onboard while three others are available in port (in process of charging). The fifth container entering the ship is the one that was the first, now fully charged in the meantime.

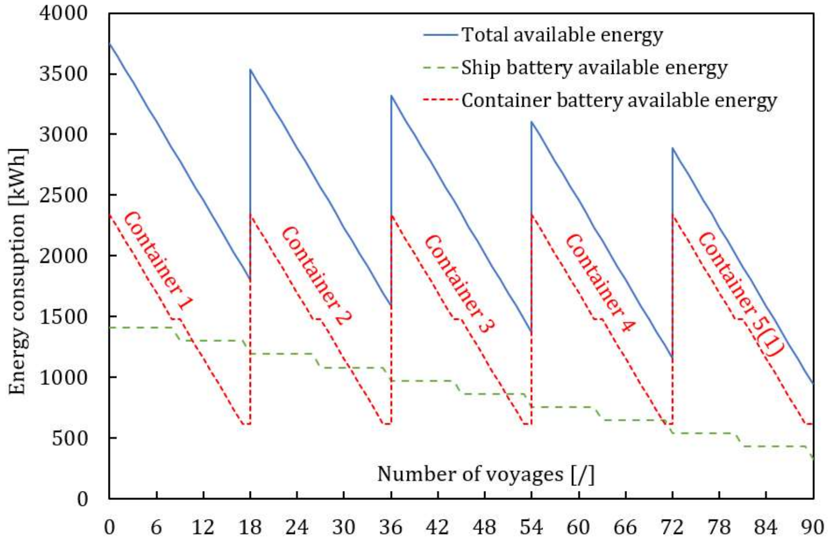

Fig. 5 – *Energy consumption of the electric ship.*

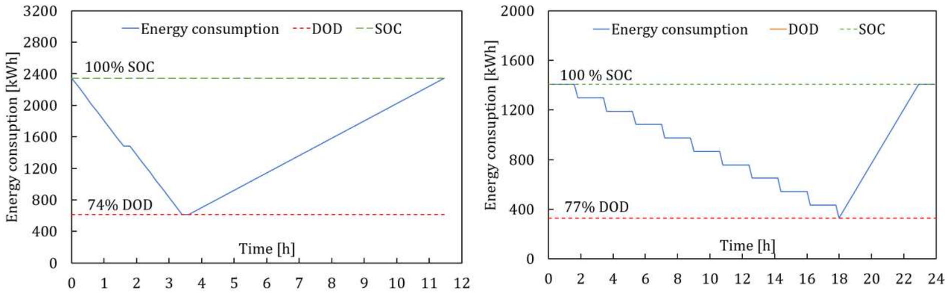

Fig. 6 – *Energy consumption: MCBP (left) and IHBP (right).*

5. Conclusion

Given the UNESCO status of the Bay of Kotor along with national and EU environmental goals, the paper delivers the potential pathway towards the onboard decarbonization of the most energy demanding ferry that operated in the Bay of Kotor, on a regular route for over a decade. In order to achieve that, authors proposed a solution for the electrification of the prototype ferry into the electric ship. It consists of installing IHBP and additionally, MCBP, classed for maritime application. MCBP is intended to be embarked onboard, used for navigation, disembarked when discharged and charged onshore. Movement would be carried out using a trailer. Both packs enable continuous operation without charging for 5 hours and 12 minutes or 26 voyages between ports. The traditional diesel propulsion to electric drive conversion results in a weight excess of 10.71 t, or 7.19% of the DWT. Electrification comes with the reduction of ship capacity. DWT is reduced by the weight of 5-6 vehicles (assuming they weigh around 2 t per vehicle), while in terms of space, 2 vehicles are removed, out of 49. On the other hand, the proposed solution relieves the ports and the bay of the harmful onboard emissions as a product of the operation of the largest ferry. Nevertheless, the weight of the batteries still presents an issue when compared to the traditional diesel power.

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