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Towards environmentally friendly short-sea transportation via integration of renewable energy sources in the ship power systems

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ABSTRACT

Reduction of fuel consumption and lowering harmful gas emissions are among the most important research topics in marine transportation. The latter particularly refers to the vessels that operate within highly inhabited areas like short-sea vessels. This paper deals with the techno-economic assessment of the implementation of renewable energy sources in the short-sea shipping sector, where Croatian ro-ro passenger fleet is taken as a test case. In this sense, the aim of the paper is to identify preferable power system configuration that reduces ship emissions (CO_2, NO_X, SO_X, particulates) at acceptable costs. Firstly, realistic operating profile of ro-ro passenger ships is analysed and their annual emissions are evaluated by assessing total fuel consumption and multiplying it by relevant emission factors. Secondly, renewable energy potential in the Adriatic Sea and Croatian energy mix are reviewed. Third, the techno-economic analysis of conventional power systems with a diesel engine as a prime mover, and proper alternatives is done. Finally, it is found that electrification of short-sea shipping sector is recognized as a promising option to reduce environmental footprint and operative costs of the ship over its lifetime.

Keywords: short-sea shipping, ship power systems, renewable energy sources, environmental footprint, fuel consumption, operative costs.

NONMENCLATURE

Abbreviations

ECA	Emission Control Area
GHG	Greenhouse Gas
IMO	International Maritime Organization
LCA	Life-Cycle Assessment
LCCA	Life-Cycle Cost Assessment
PTW	Pump-to-Wake
PV	Photovoltaic
RES	Renewable Energy Source
WTP	Well-to-Pump

Variables

A	area (m^2)
BC	battery capacity (kWh)
BP	battery price (€/kWh)
DP	diesel price (€/kg)
EC	energy consumption (kWh/km)
EF	emission factor (kg emission/kg fuel)
EP	electricity price (€/kWh)
E_{rad}	solar irradiation (MJ/m^2)
FC	fuel consumption (kg/km)
IC	investment cost (€)
l	trip length (km)
$LCFC$	life-cycle fuel cost (€)
$LCMC$	life-cycle maintenance cost (€)
LT	lifetime (year)
N	number of trips (-)
P	power (kW)
SFC	specific fuel consumption (g/kWh)
t	operational time (h)
TE	tailpipe emissions (kg/h)
v	ship speed (km/h)
x	share of a power source (-)

1. INTRODUCTION

One of the most important environmental problems is atmospheric pollution caused by the extensive use of fossil fuel [1]. Although among different transportation modes the road transport is the major contributor to the air pollution, the environmental impact of maritime transport should not be neglected. The fossil fuel combustion causes exhaust gas that comprises of harmful emissions such as nitrogen oxides (NO_X), sulphur oxides (SO_X), particulate matter (PM), carbon monoxide (CO) as well as greenhouse gases (GHGs) that refer to carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) [2]. While the GHGs have a major influence on the environment by causing global warming [3], emissions of NO_X, SO_X and PM negatively affect human health causing pulmonary diseases and other health issues [4]. Since the ships engaged in the short-sea shipping such as ro-ro passenger ships (i.e. ferries) spend much more time near ports and populated cities, their effect on people is more pronounced compared to the long-distance shipping [5].

In order to control exhaust emissions, the International Maritime Organization (IMO) set relevant standards within the International Convention for the Prevention of Pollution from Ships (MARPOL) [6]. By establishing several Emission Control Areas (ECAs), IMO regulated emissions in specific areas where limitations are stricter than elsewhere [7]. According to the MARPOL Annex VI, SO_X emissions are controlled by setting the limit on sulphur content in the fuels used in ECAs and globally, while NO_X limits are set for diesel engines depending on the engine maximum speed. The Tier I and the Tier II standards are global, while the Tier III standards apply only to NO_X ECAs [8]. Regarding the GHG emissions, their main gas, CO_2, is regulated by the Energy Efficiency Design Index (EEDI) within the energy efficiency regulation introduced by IMO in 2011 [9]. There are no explicit PM emission regulations.

Shipping emissions reduction can be achieved by the integration of renewable energy sources (RESs) in a ship power system. This leads to the electrification of ships, where the share of renewables is directly dependent on the way the electricity is generated. There are different variations of an electric ship: a plug-in hybrid, a hybrid with the battery system assisted by a diesel generator, a fully electric ship with a battery supplied by grid and/or PV (photovoltaic) cells, etc. [10]. A detailed review on alternative power system configurations is presented by Perčić et al. in [11]. Full electrification of a ship represents a viable solution for future shipping due to commercially available technology and the absence of exhaust gases. One of the issues that confront the larger exploitation of electric ships is the high investment cost.

The aim of this paper is to perform a techno-economic assessment of the implementation of RESs in coastline navigation, where a ro-ro passenger ship is taken as a test case. The performed analysis of annual tailpipe emissions (CO_2, SO_X, NO_X and PM) of the complete Croatian fleet is done, where the ship with average annual tailpipe emissions is identified and adopted for further analysis. Perčić et al. [11] already performed Life-Cycle Assessment (LCA) and Life-Cycle Cost Assessment (LCCA) of the PV cells-battery-powered ship in comparison to the diesel engine-powered ship and concluded that the alternative is a better solution from the environmental and economical point of view. However, they focused on the fully electric ship, while in this paper, a combination of a diesel generator and implementation of a RES in a battery system is considered.

2. THE POTENTIAL OF RES APPLICATION IN THE CROATIAN SHIPPING SECTOR

According to the International Energy Agency [12], the share of individual sources in the Croatian total energy supply is presented in Fig 1.

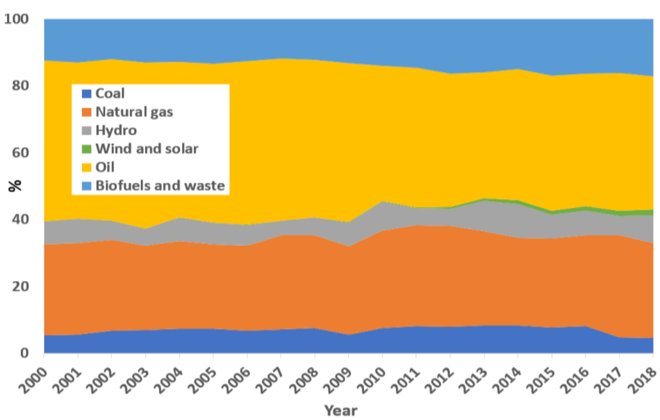

Fig 1. The total energy supply in Croatia by sources.

Through the years, oil is the most dominant source used for energy supply. However, in the last decade, its share reduces, while the very slight growth of the renewables is noticeable. In the structure of the Croatian electricity sold to the end-customers in 2018, Fig 2, the share of renewables used for electricity generation is around 40% [13]. Even though Croatia generally has a great potential of using the RESs, one should find a proper way how to use them for power generation onboard ships.

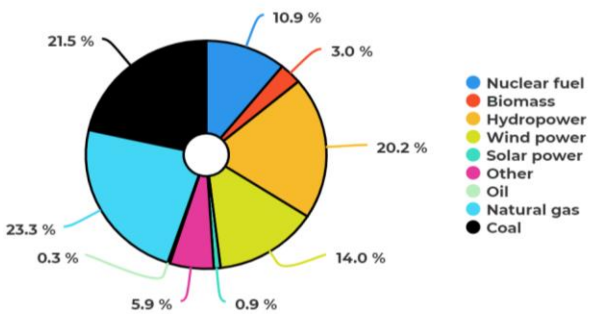

Fig 2. Croatian electricity mix in 2018

In the Adriatic Sea, the average wind power density varies from 100-200 W/m^2 [14], which is not suffecent to ensure enough power for ship propulsion. Solar energy is, however, more investigated for onboard energy generation, and its exploitation can be achieved by the installation of the PV cells on the ship deck. Off-grid PV system needs a rechargeable battery for use when there is little or no output from the PV system [15]. The Croatian coastline is very sunny with the mean annual irradiance from 5,040 MJ/m^2 to 5,760 MJ/m^2 [14], which represents a potential to use solar energy for onboard energy generation. Since this energy is, obviously, not sufficient to cover ship propulsion needs completely, in this paper the combination of the PV system, battery and diesel generator is investigated and different scenarios of using the power sources are analysed.

3. METHODOLOGY

3.1 The analysis of the Croatian ro-ro passenger fleet

The analysis is focused on the energy needs and environmental impact of the Croatian ro-ro passenger fleet operated by a national shipping company [16]. The analysis procedure is presented in Fig 3. In the first step, the fleet schedule is investigated to obtain the data on the annual number of round trips (N_A) and average duration of a trip (t) [16]. Since the operational speed differs from the design speed (v_{de}), in the second step the average speed (v_{ave}) is calculated based on the average duration of a trip and its length, while in the third step the main and auxiliary engine power are obtained for each ship [17]. Since a ship power is nearly proportional to the cube of its speed, the average main engine power ($P_{ME,ave}$) was calculated by the following formula:

$$P_{ME,ave} = (P_{ME} \cdot 0.8) \cdot (v_{ave}/v_{de})^3 \qquad (1)$$

The average load of the auxiliary engine ($P_{AE,ave}$) is estimated at 50%. By summing up $P_{ME,ave}$ and $P_{AE,ave}$, the total average ship power (P_{ave}) is calculated. The energy consumption per distance (EC) is then calculated by dividing the P_{ave} with v_{ave}.

The fuel consumption per distance (FC) is calculated by multiplying EC with specific fuel consumption (SFC). Since all the considered ships are diesel-powered vessels, the SFC is assumed to be 0.215 kg/kWh.

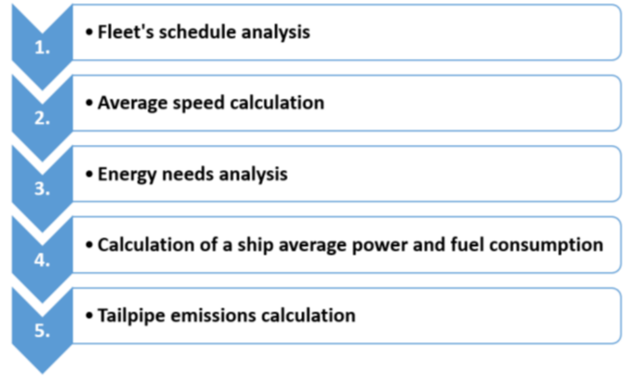

Fig 3. The steps in the analysis of the considered fleet

In the fifth step, the annual SO_X, NO_X, CO_2 and PM emissions are calculated by multiplying the annual fuel consumption (FC_A) with the emission factors (EF):

$$TE_i = FC_A \cdot EF_i \qquad (2)$$

where the subscript i refers to any emissions. Then, LCAs and LCCAs are performed for the different scenarios of using the PV system, battery and diesel generator.

3.2 LCA

The LCA is performed by means of GREET 2019 software. Emissions released during the life-cycle of a ship can be arranged into three phases:

- WTP (Well-to-Pump) phase refers to a fuel cycle (from the extraction of raw material, production of fuel and transport to the refuelling station),
- PTW (Pump-to-Wake) phase refers to the use of fuel in a power system which causes the tailpipe emissions,
- Manufacturing phase refers to the manufacturing process of the main elements in a power system and their related released emissions.

3.3 LCCA

The LCCA takes into account the total life-cycle costs of a ship power system. These costs include investment cost, the cost of fuel and the maintenance cost accompanied with the replacement cost of the main parts of the power system [18].

4. INTEGRATION OF SOLAR ENERGY IN A SHIP POWER SYSTEM

The results of the performed analysis, Fig 4 and Fig 5, revealed the environmental footprint of the considered fleet with annual emissions of 60,230 t of CO_2, 1,150 t of NO_X, 49.6 t of SO_X and 19.6 t of PM.

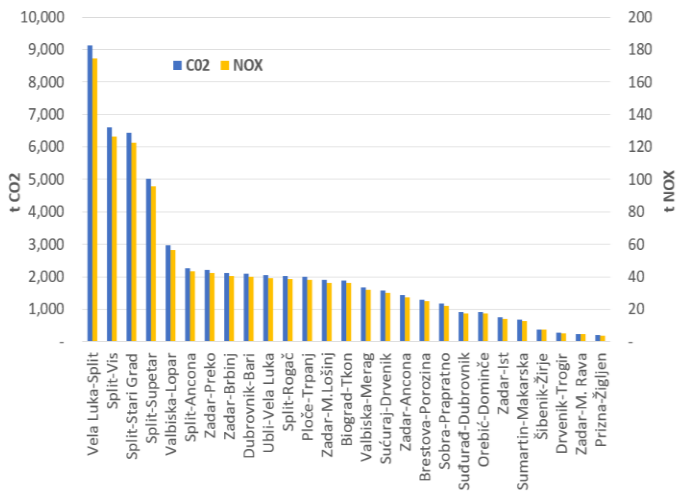

Fig 4. Annual CO_2 and NO_X emissions

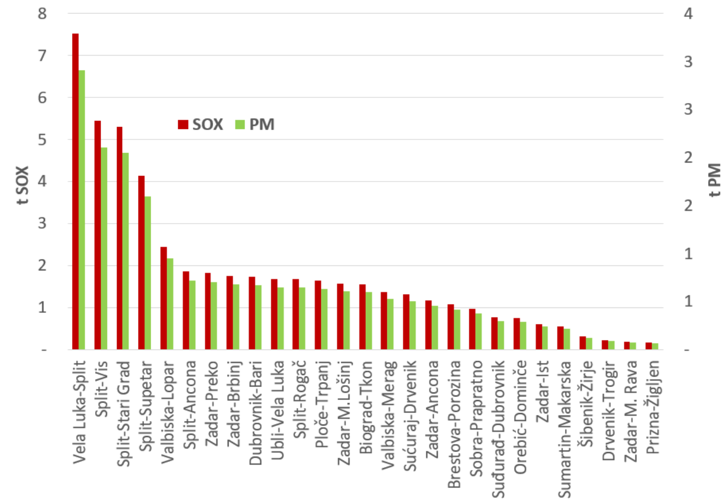

Fig 5. Annual SO_X and PM emissions

A ship power system with a Lithium-ion battery, a PV system and a diesel generator is analysed and the results are illustrated on the selected ship with the average annual *TE* and it operates between Ploče and Trpanj ports in Croatia. The ship's particulars are obtained shown in Table 1.

Table 1 The ships' main particulars

Length between perpendiculars, L_{pp} (m)	89.1
Breadth, *B* (m)	17.5
Lenght of the round trip, l_{rt} (km)	30
Duration of a round trip, t_{rt} (h)	2
Annual number of round trips, N_A	1,740
Lifetime, *LT* (year)	20
Average speed, v_{ave} (km/h)	15
Average power, P_{ave} (kW)	830
Energy consumption, *EC* (kWh/km)	55.3
Fuel consumption, *FC* (kg/km)	11.9

The power system consists of the diesel generator, the battery which is charged from the Croatian power grid, and the PV system which converts solar energy into electricity. In this paper, the several different scenarios regarding the share of power source used for energy generation are investigated and the shares of diesel, battery and solar energy are denoted as x_d, x_b and x_s.

The PV cells are usually placed on the deck horizontally and due to that, the installation area (*A*) is limited with the dimensions of a ship. For the considered ship, the available area is estimated at around 900 m^2. Besides *A*, the power output of a PV system (P_{PV}) depends on its efficiency (η) (17% [11]), and on solar irradiation (E_{rad}), which its annual average value for the area of navigation and the horizontally placed PV cells is equal to 5,557 MJ/m^2 [14]. The P_{PV} is calculated as follows:

$$P_{PV} = \frac{\eta \cdot E_{rad} \cdot A}{t_{rt} \cdot N_A}. \tag{3}$$

The battery is charged with the electricity onshore and with the electricity generated by the PV system and a diesel generator during the ship operation. Its capacity (*BC*) needs to be sufficient to ensure the ship operation on a round trip. Due to safety reasons, the capacity is increased by 20% and calculated with the equation:

$$BC = 1.2 \cdot EC \cdot l_{rt}. \tag{4}$$

4.1 LCA

Processes included in the LCA of the power system are presented in Fig 6. The WTP phase of diesel comprises of the stationary processes, which are obtained from the GREET 2019 database, and the transportation processes, which are modified depending on the trip distance, i.e. the crude oil is transported by a tanker for 4,000 km, while the diesel is transported by a tank truck for 450 km up to the Ploče port. The WTP emissions related to the electricity part of the power system considers emissions released from the process of the Croatian electricity generation, Fig 2.

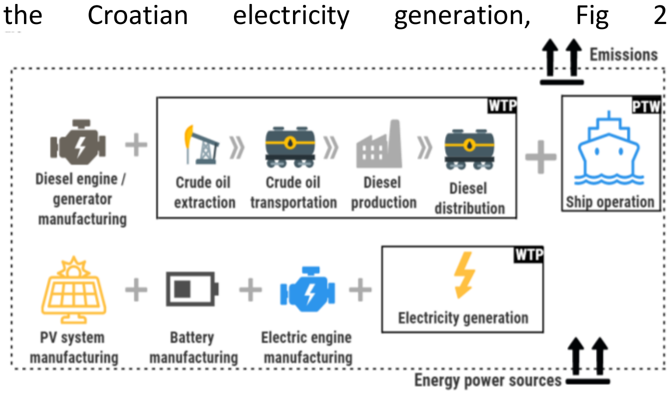

Fig 6. Processes included in the LCA

The only input for the environmental assessment of the power system's main elements (diesel generator/engine, electric engine, battery and PV system), is the weight of the materials from which these elements are constituted. The weight of the diesel generator/engine, electric engine and the battery are calculated as described in [18], while the calculation of the PV system's weight is presented in [11]. In the scenario when only diesel is used, it is assumed that the diesel engine is introduced into the power system instead of the diesel generator.

years (169 €/kWh), and the maintenance of the PV system, which annual value is assumed to be 20% of the capital cost [18].

4.3 *Results and discussion*

Considered scenarios observed in this paper are presented in Table 2. In the D0 scenario, the fully electric ship with only a battery and PV system is used, while in the D100 scenario, the only diesel engine is used. Other scenarios combine different shares of diesel, while the power output of a PV system remains the same.

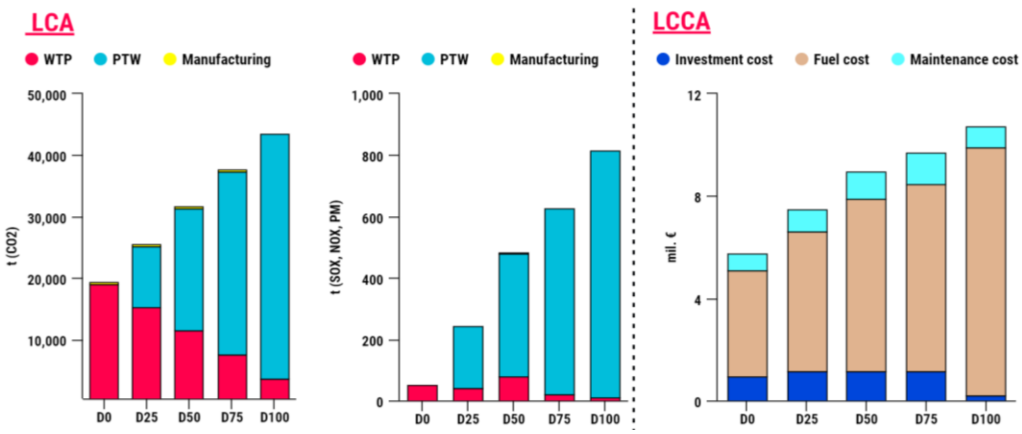

Fig 7. The LCAs and LCCAs results

The PTW emissions are released only when the ship is powered by diesel. These tailpipe emissions are already calculated by the methodology in section 3.1.

4.2 *LCCA*

The cost of a diesel engine/diesel generator is calculated with the conversion factor of 250 €/kW, while the cost of a PV system is calculating with the conversion factor of 1,116 €/kW [11]. Besides the battery, the investment cost of a battery power system includes costs of electric engine and associated equipment, and its calculation is presented in [18]. The life-cycle fuel cost of a power system ($LCFC_{PS}$) is calculated according to the equation:

$$LCFC_{PS} = LT \cdot N_A \cdot l_{rt} \cdot (x_d \cdot FC \cdot DP + (1 - x_d) \cdot ((1 - x_s) \cdot EC \cdot EP)), \quad (5)$$

where *LT* denotes ship lifetime, N_A refers to the annual number of round trips, l_{rt} refers to the length of a round trip, *FC* denotes the fuel consumption, *DP* represents the Croatian diesel fuel price (0.78 €/kg), *EC* denotes energy consumption, while the *EP* refers to the Croatian electricity price (0.078 €/kWh). The life-cycle maintenance cost of the power system refers to the maintenance of the diesel part of the power system (0.014 €/kWh), the replacement of the battery after 10

Table 2 Considered scenarios

Scenario	Power source's share		*EC* (kWh/km)		
	x_d	$x_b + x_s$	Diesel	Battery	PV
D0	0%	100%	0	50.80	4.53
D25	25%	75%	13.83	36.97	4.53
D50	50%	50%	27.67	23.13	4.53
D75	75%	25%	41.50	9.30	4.53
D100	100%	0%	55.33	0	0

The LCA and LCCAs are performed for each scenario and the results are presented in Fig 7. The LCA results revealed that the most environmentally friendly option is the fully electrified ship, i.e. the D0 scenario. Regarding the replacement of the D100 scenario with the D0 scenario, a significant reduction of CO_2 emissions of 55.5% and other harmful emissions (NO_X, SO_X and PM) of 93.5% can be achieved. According to the LCCA results, the scenario D0 represents the most cost-effective scenario with 46.3% lower cost in comparison to the D100 scenario. It can be noticed that with the increase of x_d, the life-cycle costs and emissions also increase.

5. CONCLUSION

The integration of RES into ship power systems is investigated and the results are illustrated on the vessel belonging to the Croatian ro-ro passenger fleet. Firstly, the environmental footprint of the entire Croatian ro-ro passenger fleet was analysed where the ship with average analysed tailpipe emissions (CO_2, NO_X, SO_X and PM) is selected. Then, LCA and LCCA for the different RES share scenarios were performed. The analyses indicated that the most environmentally friendly and the most cost-effective scenario is the one with only a battery and PV cells implemented onboard, i.e. the full electric ship. The research can be extended by more detailed analyses of total costs via different ship retrofit investment scenarios and influence of interest rates, effect of potential emission allowance scenarios, etc.

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