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Reduction of CO_2 emissions of inland passenger and cargo vessels by alternative power system configurations

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ABSTRACT

Increased social awareness on the greenhouse gases led to climate agreements setting their strict reduction targets. In order to achieve decarbonization of the shipping industry, some technical measures can be applied, such as replacement of classical ship power system with diesel engine as a prime mover with some alternative solution. This paper investigates the applicability of alternative power system configurations that can be implemented on board passenger and cargo ships from Croatian inland waterway fleet. The environmental impact of three different potential power system configurations (diesel engine-powered ship, battery-powered ship and photovoltaic cells-battery-powered ship) was investigated through the Life Cycle Assessment (LCA) by means of GREET 2019 software. The comparison identified the photovoltaic cells-battery-powered ship configuration as the most environmentally friendly power system configuration.

Keywords: inland waterway transportation; LCA; carbon footprint; ship power system

NONMENCLATURE

Abbreviations	
BAT	Battery-powered ship
C	Cargo ship
CF	Carbon footprint
DE	Diesel engine-powered ship
GHG	Greenhouse gas
LCA	Life cycle assessment
P	Passenger ship
PTW	Pump-to-Wake
PV	Photovoltaic
PV-BAT	Photovoltaic cells-battery-powered ship
WTP	Well-to-Pump
WTW	Well-to-Wake
Variables	
A	Area (m^2)
E_{PV}	Electric power from PV system (MJ)
E_{rad}	Annual solar irradiation (MJ/m^2)
Symbols	
η	Efficiency (-)

1. INTRODUCTION

In order to mitigate the problem of the global warming, the global community needs to reduce Greenhouse Gases (GHGs) generated by human activities. These gases refer to carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases. Their increased concentration in the atmosphere causes the greenhouse effect leading to the global warming and climate changes [1]. Since the fuel oil combustion represents the most important source of GHGs, the energy and the transport sectors contribute the most to this pollution [2]. According to the Third GHG Study conducted by the International Maritime Organization (IMO), in 2012 the international shipping was responsible for 2.1% of global GHGs. Presented

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forecasts indicate that reported percentage could grow up to 50%-250% by the end of 2050, depending on economic growth and energy development [3]. In order to ensure emission control, IMO established several Emission Control Areas (ECAs) where emission requirements are stricter than outside of them [4]. Furthermore, IMO has obliged ship-owners and ship-operators to reduce fuel oil consumption in order to achieve goal of GHG reduction from international shipping, according to which at least 70% of annual GHGs need to be reduced by 2050 compared to 2008 [5].

The investigation of shipping emissions and their impact on the environment is primarily focused on seagoing vessels and less on the inland waterway vessels. The inland navigation is, together with road and rail transport, one of the main three land transport modes and it can be considered as the most cost-effective and safest mode of transport [6]. However, due to frequent exposure to highly inhabited areas, emissions from inland navigation should not be ignored [7].

To achieve the 2050 GHG goal, the CO_2 emissions from shipping should be reduced by a set of technical and operational measures. The released CO_2 can be quantified by Carbon Footprint (CF) calculation which refers to a measure of the total CO_2 emissions that are caused by an activity or are accumulated over the life stages of a product and it can be expressed in tons of CO_2 or in tons of CO_2 equivalent (CO_2-eq) [8]. The estimation of the ship's CF through its lifetime can be achieved by performing Life Cycle Assessment (LCA) [9]. Some of the technical CF reduction measures are the replacement of the fuel oil with alternative fuels and the replacement of the conventional propulsion system (diesel engine-powered ship) with hybrid propulsion system (HPS) which is characterized by the use of different types of power sources [10]. Renewable energy sources for offshore power generation are also leading to the decarbonization of the maritime sector [11], [12], [13]. Ghenai et al. [14] presented a ship whose HPS consists of photovoltaic (PV) system, fuel cells and diesel engine, and its application onboard resulted in lower emissions in contrast to emissions released from the ship powered only by a diesel engine. Perčić et al. [15], [16] investigated alternative marine fuels and power systems in the short-sea shipping sector and identified electrification as the most environmentally friendly and cost-effective decarbonization solution. The fully electric ferry is presented by Gagatsi et al. [17], where the advantages and limitations of these ships are presented, such as the battery capacity, its price, weight and charging as well as sailing distance.

The aim of this paper is to investigate the applicability of different power system configurations for the retrofit of two different ships engaged in the Croatian inland waterway sector. By performing LCA comparison of the selected power system configurations, the most ecological one is highlighted. It should be noted that some aspects of battery analysis are omitted in this paper, such as the battery thermal management. However, by considering the sea as the unlimited cooling tank, the battery can easily be cooled down.

2. SHIPS PARTICULARS

Selected ships are the cargo ship and the passenger ship with main particulars presented in Table 1, [18]. Both ships are equipped with high-speed four-stroke diesel engines with diesel-mechanical propulsion.

Table 1 Main particulars of the selected ships

	Cargo ship	Passenger ship
Length overall (m)	75.9	13.2
Breadth (m)	9.0	4.12
Deadweight (t)	967	15.72
Main power (kW)	855	236
Auxiliary power (kW)	100	-
Total power (kW)	955	236

The cargo ship, Fig 1, is mostly used to transport oil between the two Croatian refineries, and at an average distance of about 223 km it performs 20 round trips annually.

Ship speed is dependent on several factors, as well on river speed and direction of navigation (upstream and downstream). The average speed of a cargo ship of this size is equal to 14.4 km/h, with the average main engine load equal to 75% of power installed [20], while the average load of the auxiliary engines is estimated to be 50% of auxiliary power installed. The average power of the ship is the sum of the average power of main and auxiliary engines.

Fig 1 Analysed cargo ship [19]

With an average river speed of 1 m/s [21], the estimated average duration of the upstream trip is 20.5 h, and of the downstream trip is 12.5 h. The fuel oil consumption of the ship is calculated by multiplying the energy consumption with specific fuel oil consumption. As proposed by Rudan et al. [22], for high-speed engines this value is assumed to be 215 g/kWh.

The passenger ship, Fig 2, operates in the Krka National Park and it usually sails on 5 km long route. On annual basis, the ship sails around 2,190 round trips [23]. The river speed is very low, so it is not considered. With the average speed of 15 km/h, it takes around 20 minutes for a one-way trip. It is assumed that the ship operates at 70% of the total installed power.

Fig 2 Analysed passenger vessel [23]

3. METHODOLOGY

3.1 LCA

In this paper, LCAs are performed by means of GREET 2019 software, while the focus was directed on the emissions released through the life cycle of power system configurations. Processes of raw material recovery, production of the power source and its supply to the vessel are referred as “Well to Pump” (WTP), while WTP processes and use of power source in vessel operations (known as “Pump to Wake” (PTW)) as “Well to Wake” (WTW). The WTW emissions and emissions released during the manufacturing process of the power system configuration represent the total CF of that configuration.

3.2 LCA of diesel engine-powered ship

The first option considered in this paper is to retrofit the selected ships with new MAN high-speed four-stroke diesel engines with details presented in Table 2.

LCA of diesel engine-powered ships includes processes of diesel engine manufacturing, crude oil recovery and its transportation to a refinery, diesel refining, distribution and combustion of diesel in the ship engine, Fig 3.

Table 2 Selected engines [24]

	Cargo ship	Passenger ship
Selected engine	MAN D2862 LE444	MAN D2676 LE461
Engine power, kW	735	147
Engine mass, kg	2,270	1,215
Number of engines	1	2

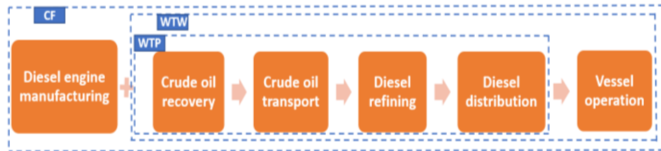

Fig 3 Life cycle of the diesel engine-powered ship configuration

The environmental impact of diesel engine was assessed by observing its manufacturing process and considering the weight ratios of material contents in the engine as proposed by Jeong et al. [25].

WTP emissions refer to fuel oil production and distribution, where all analysis parameters are adapted for the case study of Croatia.

PTW emissions, i.e. emissions released due to the combustion of diesel, are calculated by multiplying the fuel oil consumption with the emission factors [26]. To evaluate the contribution to the greenhouse effect from different GHGs, the Global Warming Potential (GWP) has been developed. It represents a measure of how much energy the emission of one ton of a gas will absorb over a given period, relative to the emission of one ton of CO_2. The time range usually used is 100 years and typically, GHGs are reported in CO_2-eq [27].

3.3 LCA of battery-powered ship

The battery-powered ship, where only a Lithium-ion (Li-ion) battery is installed on board, represents a second option for retrofitting the selected ships. Total CF of this configuration consists of the WTP of electricity and battery manufacturing process since during operation ship does not release gases, Fig 4.

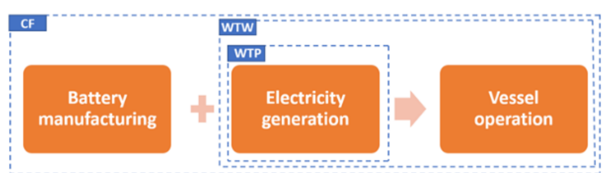

Fig 4 Life cycle of the battery-powered ship configuration

It is assumed that the ship is powered by the electric motor and that the power needs (for the existing ship) remain unchanged. Due to losses, the required power supplied by the battery should be increased by 10%. Due to gradual battery degradation (reduction of capacity up to 20%), the required battery capacities are increased by 25% to ensure the vessel's necessary range without recharging the battery. Since the typical power density of Li-ion battery is around 0.25 kWh/kg, the weights of batteries were calculated [28], and the battery manufacturing process parameters are obtained from the GREET 2019 database.

The WTP of electricity refers to the process of electricity generation. The data on main energy sources for Croatian electricity generation are obtained from [29]. In order to describe the electricity generation process in GREET 2019, data on the Non distributed U.S. Mix were combined with shares characteristic for Croatia, Fig 5.

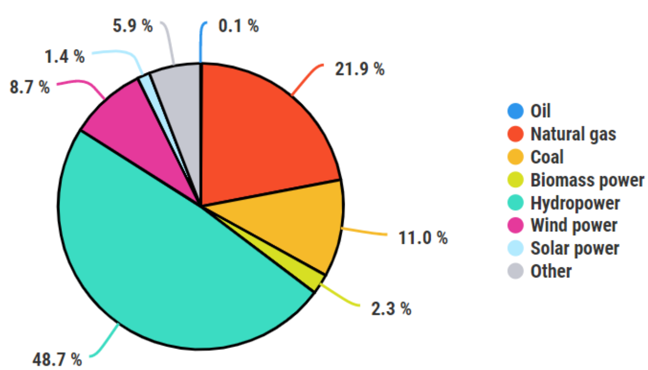

Fig 5 Croatian electricity generation mix

3.4 LCA of PV cells-battery-powered ship

The third power system configuration considered for retrofit is the PV cells-battery-powered ship, which consists of a PV system implemented on board battery-powered ship. A PV system is made of PV modules, which consist of many individual interconnected PV cells. The off-grid PV system needs a rechargeable battery, which can be used when there is little or no output from PV system [30]. LCA of the PV cells-battery-powered ship considers the WTP of electricity and processes of Li-ion battery and PV module materials manufacturing, Fig 6. Like the previous one, this option also has zero PTW emissions.

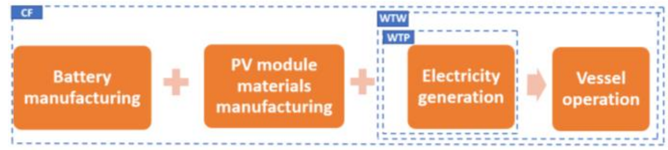

Fig 6 Life cycle of the PV cells-battery-powered ship configuration

In this investigation, the crystalline silicon (c-Si) cells were used due to their low cost, high density, high efficiency and suitability for use on horizontal surfaces [31], while their efficiency ranges between 12-19% [32]. Material's manufacturing process parameters are obtained from the GREET 2019 database.

4. RESULTS AND DISCUSSION

In the following text C denotes cargo ship, P denotes passenger ship, while the DE stands for diesel engine-powered ship, BAT refers to battery-powered ship and PV-BAT stands for PV cells-battery-powered ship.

The PTW emissions from diesel engine-powered ship configuration are shown in Table 3.

Table 3 PTW emissions from the diesel engine-powered ships

	GWP	Emission factor (g emission/kg diesel)	PTW emissions (g/km)		
			C		P
			Up	Down	
CO_2	1	3,160	42,976	26,228	7,584
CH_4	25	0.30	4.08	2.49	0.72
N_2O	298	0.08	1.16	0.71	0.20

The LCA of diesel engine-powered option considers diesel engine manufacturing process (DE), diesel production and distribution (WTP) and PTW emissions. The total CF of battery-powered ship is equal to WTP emissions of electricity generation, i.e. WTW emissions, and emission released during battery manufacturing process. In order to calculate the CF of the PV cells-battery-powered ship, emissions during the PV system manufacturing process should be added to the CF of the battery-powered ship, while the WTP emissions are reduced due to the lower energy consumption. All these results are summarized in Table 4 and in the Figure 7.

The most ecological alternative for the retrofit both cargo ship and passenger ship is the PV cells-battery-powered ship configuration since during the life cycle of configuration was released lesser GHG than other power system configuration did and therefore the total CF of this configuration is lower.

Table 4 Annual emissions released from alternative power system configurations (t CO_2-eq)

	Diesel engine-powered ship			
	WTP	PTW	DE	CF
C	30.3	311.9	0.4	342.6
P	16.0	167.7	0.2	183.9
	Battery-powered ship			
	WTW	BAT	CF	
C	156.0	34.1	190.1	
P	66.5	0.3	66.8	
	PV cells-battery-powered ship			
	WTW	BAT	PV	CF
C	138.5	34.1	3.5	176.1
P	65.8	0.3	0.1	66.2

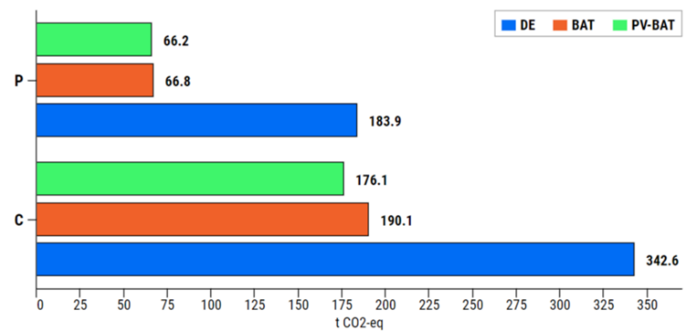

Fig 7 Annual CFs of considered ships with different power system configurations, (t CO_2-eq)

5. CONCLUSION

The applicability of different power system configurations for the retrofit of ships engaged in the Croatian inland waterway sector was investigated from the environmental point of view. The most ecological power system configuration for both ships is highlighted and, it is the one with the lowest CF.

It is necessary to mention that the accuracy of the performed LCAs can be further improved by analyzing every step in the electricity production in more detail as well other transportation types in crude oil manipulation can be considered. However, it is reasonable to expect that irrespective on the scenario, the electrification of the shipping industry will be advantageous from the environmental viewpoint.

Complete insight into the viability of considered power system configurations can be achieved by comparing them also from the economic viewpoint, which will be subject of further investigation.

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