HOLISTIC ENERGY EFFICIENCY AND ENVIRONMENTAL FRIENDLINESS ANALYSIS OF INLAND SHIPS WITH ALTERNATIVE POWER SYSTEMS

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ABSTRACT

In order to deal with the decarbonisation of the transport sector, many policies suggest the application of alternative fuels with an emphasis on the electrification, an increase in the energy efficiency of transportation modes and a shift of freight and passenger transport from road transportation to other modes of land transport such as inland waterway transport. The vessels engaged in the inland waterway transport are often outdated, powered by low-energy efficient diesel engines, operating near populated areas and thus directly impair the air quality of the nearby population. Therefore, their energy efficiency and environmental friendliness need to be improved. Furthermore, energy efficiency and environmental friendliness assessment of ships with alternative power systems represent a special issue, since such mathematical models regularly consider power systems that use fuel with carbon content only. In this paper, the retrofitting of different types of vessels (cargo ship and passenger ship) with alternative power systems (powered by electricity, methanol, natural gas hydrogen and ammonia) is considered, while the diesel power system configuration represents a baseline scenario. Their energy efficiency and environmental friendlies are assessed, considering their annual life-cycle emissions and benefit to the society, by means of the mathematical model recently published in the literature and applied to short-sea vessels only. Its applicability to other transportation modes/ship types is confirmed and differences in energy efficiency and environmental friendliness of different power system alternatives are outlined.

Keywords: inland waterway transportation, energy efficiency and environmental friendliness index, alternative fuels, LCA

1 INTRODUCTION

Global warming represents one of the most critical environmental problems nowadays. This problem results from the extensive use of fossil fuels whose combustion releases a significant amount of Greenhouse Gases (GHGs) in the atmosphere, which then trap the heat in the Earth's atmosphere, causing the greenhouse effect. The GHGs refer to the emissions of carbon dioxide (CO_2) as the main GHG, methane (CH_4), nitrous oxide (N_2O) and fluorinated gases in low concentration (UNFCCC, 2021). According to the latest climate agreement, i.e. Paris Agreement, each sector needs to contribute to the reduction of GHGs concentration on a global level (UNFCCC, 2021).

In the shipping sector, the vast majority of ships is powered by fossil fuel, whose combustion in the marine engines results in GHGs but also other emissions such as nitrogen oxides (NO_X), sulphur oxides (SO_X), Particulate Matter (PM), etc (Monterio et al., 2018). These pernicious emissions have a local character and negatively affect the nearby population with respiratory diseases and the environment through the processes of acidification and eutrophication (Kim and Chae, 2016; Zhao et al., 2021). To reduce the negative impact of shipping emissions, the International Maritime Organization (IMO) provided several emission control standards. One of them is the establishment of Emission Control Areas (ECAs), which refer to the areas with stricter emission requirements than those outside these areas (Chen et al., 2018). SO_X emission is limited based on the allowed sulphur content in the fuel, which differs for the ships that operate in ECAs or elsewhere. NO_X emission is controlled by three standards (Tier I, Tier II and Tier III), and it depends on the engine's maximum operating speed. Tier I and Tier II refer to the global area of navigation, while Tier III is related to ship operation in ECAs (IMO, 2021). The shipping GHG emissions from the shipping sector are controlled via energy efficiency regulation, adopted in 2011. According to that regulation, each ship of GT over 400 that is engaged in international shipping needs to have the International Energy Efficiency (IEE) Certificate. Due to that, the ship has to comply with the Energy Efficiency Design Index (EEDI) requirements and have the Ship Energy Efficiency Management Plan (SEEMP). The CO_2 emissions are controlled through the EEDI, which refers to the technical measure of energy efficiency, and it is expressed as a ratio of the released CO_2 emissions from the marine engines and transport work, i.e. benefit for the society. Calculated EEDI for each new ship need to be equal or lower than the required EEDI (MEPC, 2011). To expand the energy efficiency requirements on the existing ships, in 2021, IMO introduced the Energy Efficiency Existing Ship Index (EEXI), which will enter force from January 2023 (DNV, 2022). Although these emission control requirements are beneficial, they are mainly focused on long-distance ships engaged in international shipping and not on the ships that operate near the shore (short-sea shipping) and in the inland navigation and whose negative impact on the local population is more pronounced.

The decarbonisation measure that results in the great reduction of GHGs emissions but also in the reduction of other pernicious emissions is the replacement of the conventional power system with an alternative one, fueled with alternative fuel, preferably with lower carbon, nitrogen and sulphur content than the currently used fossil fuel such as Heavy Fuel Oil (HFO)or Marine Diesel Oil (MDO) (Ait Allal et al., 2019; Hansson et al., 2019). Due to lower carbon content and availability, natural gas and methanol are widely investigated as alternative marine fuels (Ammar et al., 2019; Fan et al., 2021). However, they are still fossil fuels and their use results in shipping emissions. The most environmentally friendly alternative solution is the application of power systems that promotes zero-emission shipping (i.e. electricity, ammonia, hydrogen), especially for use on vessels that are engaged in the inland waterway sector and short-sea shipping sector (Gagatsi et al., 2016; Perčić et al. 2022b). In their studies, Perčić et al. (2020a; 2020b; 2021a; 2021b) investigated alternative powering options for both short-sea shipping and inland navigation in Croatia. The comparative Life-Cycle Assessment (LCA) and Life-Cycle Cost Assessment (LCCA) of different power system configurations indicated that for ro-ro passenger ships operating in the Adriatic Sea, the full electrification with only a battery as a power system represents the most environmentally friendly and cost-effective option. However, when investigating inland navigation and different types of vessels, the results differ. For each of them, electrification represents the most environmentally friendly solution, but an LCCA comparison showed that for some vessels the methanol, diesel and electrification represent great economic solutions.

Inland navigation refers to the mode of transport of passengers and freight by vessels via inland waterways (canals, rivers, lakes, etc.) (Weigmans, 2015). In Europe, the majority of the freight and passenger transport is divided between road transportation (76%) and railways (18%), while inland waterway transport makes up only 6% (Sys, 2020). However, the adopted European Strategy for Low-Emission Mobility encourages increasing the efficiency of the transport system together with a shift towards lower emissions transport modes, such as inland navigation, the use of alternative fuels with an emphasis on electrification, and a transition to zero-emission vehicles (EC, 2020). In addition to the European Strategy for Low-Emission Mobility, many other EU countries are covered by their national policies, just like Croatia. Within the Low-Carbon Development Strategy of the Republic of Croatia until 2030 with an outlook to 2050, GHGs reduction measures that apply to the transport sectors are considered: the use of low-carbon fuels, increasing the energy efficiency of transportation modes, and promoting the sustainable integrated transportation of passengers and freight, i.e. shifting from road transportation to railway and inland waterway transportation (MESDRC, 2021). However, the ships that navigate the Croatian inland waterway network are outdated and powered by low energy-efficient diesel engines. Therefore, before directing the shift of freight traffic from road transportation to inland navigation, the energy efficiency of these ships needs to be assessed to ensure the appropriate power system for each vessel and to further improve their environmental friendliness by the implementation of alternative power systems, whose use onboard would result in lower tailpipe emissions or with their absence. Since some alternative solutions result in no tailpipe emissions, such as electricity, hydrogen and ammonia as alternative fuels, their environmental performance needs to be assessed from the life-cycle point of view. Perčić et al. (2022b) developed a mathematical model for energy efficiency and environmental eligibility of alternative power systems implemented on three ships operating in the Adriatic Sea that combine different environmental impact categories. A similar principle can be used for the analysis of the Croatian inland waterway vessels, with minor modifications regarding the benefit for the society of individual vessels. In this paper, energy efficiency and environmental friendliness of selected inland ships were analysed for different power system configurations powered by various fuels (diesel, electricity, methanol, Liquefied Natural Gas (LNG), hydrogen and ammonia), according to the guidelines presented in a study by Perčić et al. (2022b). Their comparison highlighted the most energy-efficient and environmentally friendly power options for each considered vessel.

2 THE SELECTED CROATIAN WATERWAY VESSELS AND THE CALCULATION OF THEIR ENERGY NEEDS

The Croatian inland waterway network consists of several river streams with a total length of 787.1 km. Besides rivers, the Croatian inland navigation vessels also operate on lakes situated in the protected areas of nature and primarily are used for transport of the visitors (MSTIRC, 2020).

The Croatian inland waterway fleet consists of four groups of vessels: tugboats and dredgers, cargo ships and passenger ships. In this paper, the energy efficiency and environmental friendliness of representatives of cargo and passenger ships are investigated. They are presented in Table 1. Considered types of vessels differ in their exploitation characteristics. Speed, capacity and route are exploitation characteristics of a cargo ship, while the number of passengers transported and route corresponds to the exploitation characteristics of a passenger ship.

Tanker “Opatovac” is representative of a group of Croatian cargo ships engaged in inland navigation. It transports oil between two Croatian refineries along the waterway of the Sava River. The passenger ships in the Croatian inland waterway fleet are usually used for the transport of the tourist, either on rivers or lakes. The representative for this group of vessels is the passenger ship “Trošenj” which operates on a lake in the National

Park Krka and is used for the transportation of tourists on their route through the nature protection area. The main particulars of the selected vessels are presented in Table 2.

Table 1. The selected vessels engaged in the Croatian inland (Marine Trafic 2020; NP Krka 2020)

Vessel type	Vessel's name	Vessel's preview	Exploitation characteristics
Cargo ship	Tanker "Opatovac"		Speed, capacity, route
Passenger ship	Passenger ship "Trošenj"		Speed, number of passengers, route

Table 2. The main particulars of the selected vessels (Perčić et al., 2021b)

	Cargo ship	Passenger ship
Length overall, L (m)	75.9	13.2
Breadth, B (m)	9.0	4.12
Deadweight, DWT (t)	967	15.72
Main engine power, P_{ME} (kW)	855	236
Auxiliary engine power, P_{AE} (kW)	100	-
Total power installed, P_T (kW)	955	236

The calculation of energy needs of the considered vessels differs. The cargo ship operates on the river where the river current influences the energy needs, whether the ship is sailing upstream or downstream. The ship transports oil on a long round trip of 446 km, 20 times annually. Taking into account that the average speed of a cargo ship of this size is 14.4 km/h at 75% of the maximum continuous rating (van Essen et al., 2004), the average speed of the Sava River is 1 m/s (CMHS, 2021), and the average load of the auxiliary engines at 50% of the maximum continuous rating, the average ship power, P_{ave} (kW), is calculated according to the following equation:

$$P_{ave} = P_{ME,ave} + P_{AE,ave}, \quad (1)$$

where $P_{ME,ave}$ refers to the main engine power and $P_{AE,ave}$ refers to the auxiliary engine power. The energy consumption per distance, EC (kWh/km), is calculated by dividing P_{ave} with the ship speed, v (km/h):

$$EC = \frac{P_{ave}}{v} \quad (2)$$

The considered passenger ships operate on the lake. The duration of a one-way trip is 20 minutes, while the average speed is 15 km/h (NP Krka, 2020). It is assumed that the ship operates at 70% of the total installed power. Its energy consumption per distance is calculated with eq. (2). Fuel consumption per distance, FC (kg/km), for both vessels is calculated with a general equation:

$$FC = EC \cdot SFC \quad (3)$$

where SFC refers to specific fuel consumption (kg/kWh), whose value is specific for each considered power system configuration.

3 METHODOLOGY

3.1 The analysis of efficiency and and environmental friendliness of ships

The energy efficiency and environmental friendliness of considered inland vessels are analysed with the mathematical model developed by Perčić et al. (2022a). This model for simultaneous assessment of energy efficiency and environmental eligibility of ships refers to the calculation of energy efficiency and emission index (EEI), which applies not only to diesel-powered ships but also to ships powered by alternative power systems. The EEIs are calculated according to the following equation, which includes the evaluation of different emissions released by power systems considering three impact categories, i.e. global warming, acidification and eutrophication:

$$EEI = \frac{\alpha \cdot GWP + \beta \cdot AP + \gamma \cdot EP}{BS}. \quad (4)$$

In the previous equation, *GWP* denotes Global Warming Potential, *AP* refers to Acidification Potential, *EP* represents Eutrophication Potential, while *BS* refers to the benefit for the society. In this paper, the weighting factors ($\alpha = 0.095$; $\beta = 18.3$; $\gamma = 21.1$) are obtained from the study by Perčić et al. (2022a), where they correspond with the environmental impact of ro-ro passenger ships that spend much more time in ports and near populated areas than other ships, which is also the case for the inland vessels that operate through and near populated areas. Based on ship exploitation characteristics, the analysed vessels differ in considered *BS*s. *BS* of the cargo ship refers to the annual capacity of a vessel (*DWT*), which can be calculated by multiplying *DWT* from Table 2 and the annual number of one-way trips, i.e. 40. *BS* of the passenger ship refers to the annual number of visitors to the National Park where the ship is used. The average annual number of visitors in the previous 5 years is 1,030,222.20 (Imbrišić, 2022).

The evaluation of environmental impact through the released different emissions is performed by calculating *GWP*, *AP* and *EP* according to the following equations:

$$GWP = \left(1 \cdot E_{CO_2} + 36 \cdot E_{CH_4} + 298 \cdot E_{N_2O}\right), \quad (5)$$

$$AP = 1 \cdot E_{SOx} + 0.7 \cdot E_{NOx}, \quad (6)$$

$$EP = 0.13 \cdot E_{NOx}, \quad (7)$$

where *E* refer to the emissions of a particular gas.

GWP refer to 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 1 ton of CO_2. It is calculated by multiplying CO_2-equivalent (CO_2-eq) factors over 100 years (CO_2: 1; CH_4: 25; N_2O: 298) (EPA, 2021). *AP* is calculated by multiplying the emissions of a particular acidifying gas by the SO_2-equivalence factors (SO_2-eq) (SO_X: 1; NO_X: 0.7), while *EP* is calculated by multiplying the NO_X emission with the PO_4-equivalence factor (PO_4-eq) (NO_X: 0.13) (Gonçalves Castro et al. 2019). The considered emissions refer to annual emissions released through a life-cycle of a power system and they are obtained through LCA.

3.2 LCA

LCA represents a method that is often used for assessing the environmental footprint of a product through its life cycle, i..e from a process of raw material extraction to its production, transportation of a final product, its use, end-of-life treatment, recycling and final disposal (ISO 14040, 2021). In this paper, the LCAs of different ship power systems are performed by means of GREET 2020 software (GREET, 2020). The emissions released through the life-cycle of the ship's power system can be arranged into three phases. The first one is the Well-to-Pump (WTP) phase, which includes the processes of raw material recovery, production of the fuel and its transportation to the refuelling station. The second phase is the Pump-to-Wake (PTW) phase, which refers to the use of a product. The PTW emissions, i.e. tailpipe emissions (*TE*), refer to emissions released by the combustion of fuel in marine engines when a ship is operating. They are calculated by multiplying *FC* with emission factors, *EF* (g emission/kg fuel) according to the following equation:

$$TE_i = FC \cdot EF_i\ , \quad (8)$$

where the subscript *i* refers to any emissions. In this paper, only emission factors for diesel, methanol, and LNG are used (Table 3) since, during the operation of the electricity-powered ship, hydrogen-powered ship and ammonia-powered ship, there is an absence of tailpipe emissions. The third phase refers to the Manufacturing (M) phase and includes emissions released during the manufacturing process of the main elements of a power system (fuel cell, engine, battery, etc.).

Table 3. Emission factors (Jovanović et al.,2022)

	Emission factors (g emission/kg fuel)		
	Diesel	Methanol	LNG
CO_2	3,206	1,380	2,750
CH_4	0.06	0	51.2
N_2O	0.15	0	0.11
NO_X	61.21	8	0.02
SO_X	2.64	0	0.18

The annual GHG, SO_X and NO_X emissions are obtained with LCA, where the specific processes included in the LCAs and the mathematical models of implementation of alternative fuels in ship power systems are obtained from (Perčić et al., 2021b).

4 RESULTS AND DISCUSSION

In order to calculate the *EEI* that gathers different impacts on the environment, and it is applicable for ships with alternative fuels, the environmental impact analysis of the selected ships engaged in the Croatian inland waterway fleet has been done, Figure 1. In the following results, D denotes diesel, E refers to electricity, M denotes methanol, while H and A denote hydrogen and ammonia.

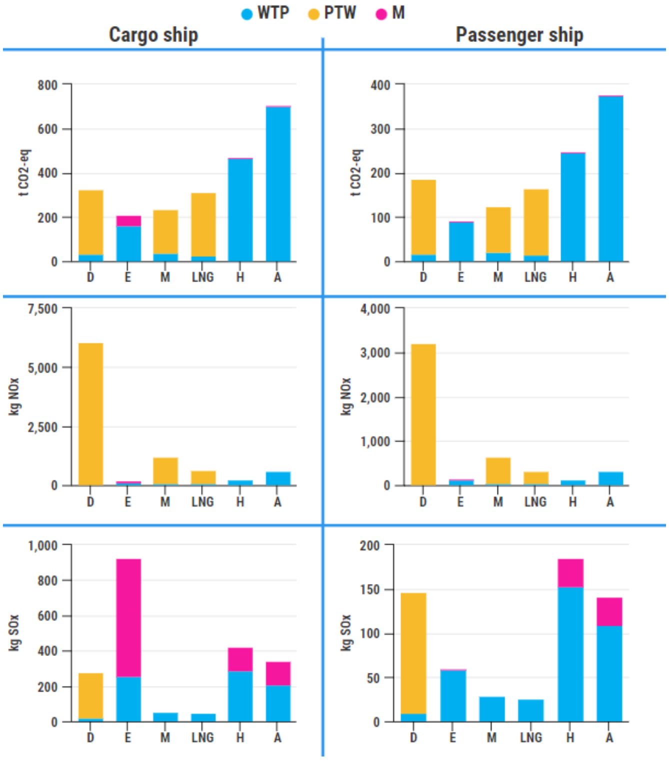

Figure 1. The comparison of annual life-cycle emissions for different power systems

The LCA resulted in the annual life-cycle GHGs, NO_X and SOx emissions for different power system configurations implemented on two different types of vessels engaged in the Croatian inland waterway fleet., Figure 1. Regarding the GHG emissions, the full electrification with only a Li-ion battery results in the lowest environmental footprint, while the power system configurations that contribute the most to global warming are the ones that use fossil ammonia and fossil hydrogen as a fuel for the Proton Exchange Membrane Fuel Cell (PEMFC). Although the latter power system configurations do not have tailpipe emissions, their production from fossil fuels results in a great amount of GHGs. Ammonia results in higher annual GHGs than hydrogen since a low-temperature PEMFC requires only hydrogen as a fuel. Therefore, ammonia needs to be processed through a cracker and a purifier before entering the fuel cell, resulting in losses.

The greatest contributor to NO_X emissions among the considered power system configurations is a diesel-powered ship since during its operation, a great amount of tailpipe NOx is released. The LCA results also showed that for cargo ships and passenger ships, different power systems are the ones with the greatest SO_X emissions. Due to the greater capacity of a battery, full electrification of the cargo ship results in the highest SO_X emissions, while for the passenger ship, the highest SO_X emission has the hydrogen-powered ship.

The obtained annual emissions and *BS* are used for the calculation of *EEI*, according to equations (4)-(7). The calculated *EEI*s for different power systems installed onboard inland waterway vessels are presented in Figure 2.

According to the results presented in Figure 2, the alternative power system configurations for both vessels result in lower *EEI* than the existing powering option, i.e. diesel-powered ship, which is the most represented power system in the shipping sector. The alternative power system that is the most energy-efficient and environmentally friendly option among those considered is full electrification with only a Li-ion battery as a power source. A fully electrified cargo ship has around 69% lower *EEI* than a diesel-powered cargo ship, while this percentage for passenger ships is higher, i.e. 83%. This is mainly due to the cargo ship's greater environmental footprint caused by greater battery capacity and the emissions released during the battery manufacturing process.

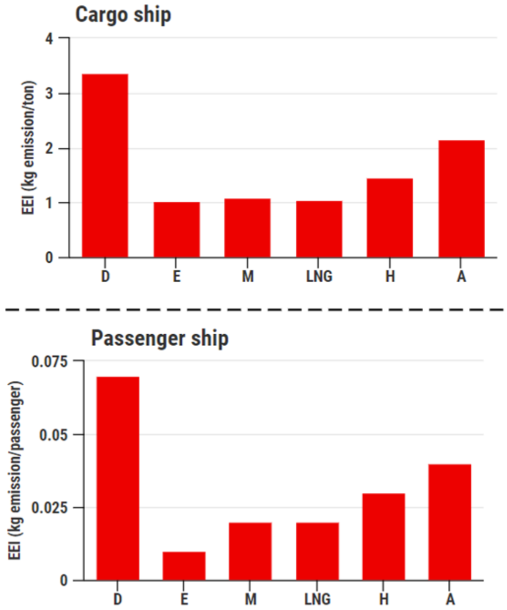

Figure 2. Calculated *EEI*s for ships with different power systems

From the decarbonization perspective, the applications of fossil hydrogen and ammonia in a ship power system are not viable solutions at this point for the reduction of GHG emissions. However, by calculating *EEI*s of different power systems onboard considered vessels, the use of fossil hydrogen and ammonia results in lower *EEI* than the diesel-powered ship, of around 57%-59% (hydrogen) and 36-38% (ammonia). This is due to the use of the weighting factors corresponding to the environmental impact of ships operating near populated areas such as inland waterway vessels do.

5 CONCLUSION

One of the strategies for decarbonization of the transportation sector is the implementation of alternative low-carbon fuels and an increase in the energy efficiency of transportation modes. Since road transport represents the greatest contributor to transportation emissions, some policies propose shifting freight and passenger transport from the road to other modes of land transport, such as inland waterways. However, the vessels engaged in the inland waterway transport are often outdated, powered by diesel engines of low energy efficiency. Therefore, before making the shift to inland navigation, the inland vessels need to be energy efficient and environmentally friendly. In this paper, the two different types of vessels (cargo ship and passenger ship) engaged in the Croatian inland waterway fleet are investigated, onboard which five different alternative power system configurations are implemented. Their energy efficiency and environmental eligibility are investigated using the mathematical model recently published in the literature, which can be applied not only to diesel-powered ships but also to alternative power systems.

Before analysing energy efficiency and environmental friendliness by calculating *EEI* for each vessel, the LCA is used for assessing the annual GHG, NO_X and SO_X emissions. Their comparison indicated that regarding the GHG and NO_X emissions, the full electrification with only a Li-ion battery as a power source represents the most ecological solution, while regarding the SO_X emissions, LNG represents the most ecological powering option.

The used mathematical model is developed for the short-sea shipping vessels. Since they operate near ports and populated areas such as inland waterway vessels, the same weighting factors are used to evaluate different environmental impacts, i.e. global warming, acidification and eutrophication. The *EEI* comparison of ships with different power systems indicated that electrification represents the best energy-efficient and environmentally friendly alternative solution among those considered, with 69% lower *EEI* than a diesel-powered cargo ship, while this percentage for passenger ships is higher, i.e. 83%. The applicability of the used mathematical model to inland waterway vessels and their different types is confirmed.

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