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Comparative life cycle assessment of battery- and diesel engine-powered river cruise ship

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ABSTRACT: Exhaust gases from marine engines are one of the major causes of marine environmental pollution. Although the researches into ship emissions are more focused on ocean-going vessels, emissions from short-sea and inland navigation also contribute to the global amount of pollutant emissions produced by combustion of fuel oil. While this share is small, short sea and inland ships usually operate in highly populated areas and consequently affect both human health and environment. In order to evaluate the environmental impact of river cruise ship that occasionally operates in Croatian inland waterways, its life cycle assessment (LCA) has been performed. Two different power system designs were investigated, i.e. lithium-ion battery-powered ship and diesel engine-powered ship. The analyses were performed by means of general LCA software GREET 2018, The analysis showed that diesel engine-powered ship emits 46.63 kg CO_2-eq/nm, versus battery-powered ship with 20.39 kg CO_2-eq/nm.

1 INTRODUCTION

Anthropogenic greenhouse gases (GHGs) are causing the greenhouse effect, and therefore the global warming. These GHGs refer to emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases (UNFCCC 2001). This air pollution nowadays represents probably one of the most important environmental problems that needs to be resolved. Along with industry and road traffic, shipping sector contributes to this problem. Exhaust gases released from combustion of fuel in marine engines are considered to be one of the major causes of marine environmental pollution. The most pernicious emissions released from the engine are CO_2, carbon monoxide (CO), nitrogen oxides (NO_X), sulphur oxides (SO_X) and particulate matter (PM) (IMO 2014). The presence of these gases has negative effect both on the environment and on the human health causing respiratory diseases.

It is fair to say that research into emissions from shipping and the wider impact on air quality as well as climate changes has been mainly directed to ocean-going vessels, and less on the inland ships and their emissions. The reason for this is mainly the general opinion that these emissions have a small contribution to total transport emissions. However, it is important to mention that inland waterway transportation is regularly realized within highly populated areas, and therefore its effect should not be ignored (Keuken et al. 2014). The inland waterway transport is, together with road and rail transport, one of the main three land transport modes. Goods are transported by ships via inland waterways, such as canals, rivers and lakes, between inland ports and wharfs (ECA 2015). Beside transportations of passengers and cargo, inland waterways are nowadays highly used for tourism purposes (Wiegmans et al. 2015).

Quantification of CO_2 emissions can be achieved by Carbon Footprint (CF) calculation. The CF term represents a measure of the total amount of CO_2 emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product (Wiedmann & Minx 2008). CF calculation serves as a tool to assess the negative impact of the CO_2 emission and it can be expressed in tons of CO_2 or in tons of CO_2 equivalent (CO_2-eq).

With the aim to increase the energy efficiency of ships, conventional power systems (diesel-mechanical propulsion) can be replaced by alternative hybrid power systems (HPS) or integrated power system (IPS), that result in reduced pollutant emissions. The HPS are characterized by the use of different types of power sources, while the main characteristic of IPS is the centralized electric power generation and the application of electric propulsion. For example, Ančić et al. (2018a) proved that ro-ro passenger ships with IPS or HPS are more energy efficient compared to the fleet average which is

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using mechanical propulsion. Kalikatzarakis et al. (2018) analyzed a tugboat powered by a hybrid propulsion plant with power supply that can be recharged with renewable shore power. That hybrid configuration has the additional challenge to determine the optimal power-split between three or more different power sources in real-time, and to optimally deplete the battery packs over the mission profile. Motivated by the extensive exploitation of electric power in ships, Kanellos et al. (2017) proposed an optimal power management method for ship electric power systems comprising integrated full electric propulsion, energy storage and shore power supply facility. Gagatsi et al. (2016) have presented a fully electrified ferry (E-ferry concept) as a new paradigm in short-sea shipping. So far, typical electric ro-ro passenger ship could use batteries as the main power source on short trips and they could be charged whilst connected to the shore power. As batteries continue to develop, the electric propulsion would replace conventional one on longer distance trips. Battery-powered ferries seem to be the most environmentally friendly, but there are limitations that are connected to high speed of a ship, long distance trips, increased time in ports due to charging the battery and capacity limitations of the electricity grid (Kullmann 2016). However, electrification of a ship results in releasing zero emissions during the operation. In order to assess the environmental impact of that ship, the emissions released from processes of electricity generation and battery manufacturing need to be considered. That can be achieved by performing Life cycle assessment (LCA). LCA provides quantification of emissions through life cycle of a specific product. This technique is evaluating the environmental impact of a product from its production, through its use and up to eventual reuse, recycling or disposal (Ling-Chin et al. 2016). The results of LCA can be presented in amount of different emissions, which are released from processes during its life cycle. This assessment also represents useful tool for comparison of different power system configurations. Such kind of research was performed by Jwa & Lim (2018). Comparative LCAs of lithium-ion (Li-ion) battery electric bus and diesel bus were completed, from extraction of fuel and generation of energy to vehicle operation. Results showed that vehicle powered by diesel engine has higher emissions than the one powered by Li-ion battery.

The aim of this paper is to perform comparative LCA of battery- and diesel engine-powered river cruise ship operating in Croatian inland waterways. The paper is structured into six sections. In the next section the methodology of LCA of the river cruise ship is presented. The third section is dedicated to LCA of diesel engine-powered ship and LCA of battery-powered ship in fourth section. The fifth section contains the results of performed LCA comparison of different power system designs and discussion. Finally, concluding remarks are drawn in sixth section.

2 METHODOLOGY

2.1 *LCA*

According to International Organization for Standardization (ISO 1997), LCA is a technique for assessing environmental impact of a product throughout its life cycle (i.e. cradle-to-grave) which includes:

- Raw material,
- Production or manufacturing,
- Use of product,
- End of life treatment,
- Recycling and final disposal.

In this paper, two LCAs are performed by means of GREET 2018 software. Processes of raw material recovery, power source production and its supply to the vessel are referred as “Well to Pump” (WTP), while WTP processes and use of power source in vessel operations as “Well to Wheel” (WTW), Figure 1. Even though the classical LCA includes disposal process of a product as a final phase of life cycle, in this paper the LCA is performed from the WTW point of view and disposal is not included into the assessment.

In this paper, the system boundary of the LCA is defined by GREET 2018, which takes into account emissions related to the main product and other products that are related to it somehow, but do not considers, for example, emissions released by building the infrastructure or vehicle manufacturing. For the river cruise ship powered by diesel engines, the LCA begins with an extraction of crude oil. After that, the crude oil is transported to refinery where it is processed into the diesel fuel. Diesel is then transported by tank trucks to the gas stations, and ultimately ends up in the vessel. Electricity generation followed by electricity transmission, distribution, battery manufacturing and ship operation constitute the life cycle of electricity as power source for battery-powered ship. The comparison of those two different power systems configurations is based on the results that represent total emissions of harmful gases throughout the entire power system configuration life cycles, Figure 2. During their life cycles, other pollutants are also released, such as NOx, particulate matter (PM), hydrocarbons (HC) and CO, but this paper follows ongoing research trends in the field of CF and is focused on the anthropogenic GHG emissions only. In order to evaluate the contribution to greenhouse effect from each of GHGs, the global warming potential (GWP) term has been developed. It represents a measure of how much energy the emission

Figure 1. WTW and WTP display of diesel-powered ship.

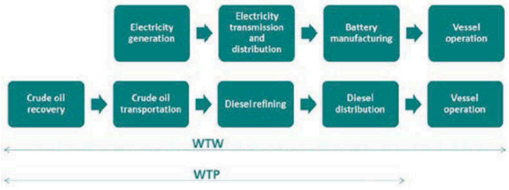

Figure 2. Life cycles of power system configurations.

of one ton of a gas will absorb over a given period, relative to emission of one ton of CO_2. The time range usually used is 100 years and typically, GHGs are expressed in CO_2-eq (EPA 2019). GHG emissions are converted into CO_2-eq by multiplying the GHG emissions with their GWP values, as prescribed in (EPA 2018). Therefore, the LCA results are expressed in unit of CO_2-eq.

Total amount of GHG emissions from battery- and diesel engine-powered river cruise ship are calculated by using default data from GREET 2018 as well as by adapting the software with the data typical for some processes in Croatia.

2.2 *Ship particulars*

The Croatian inland waterway network consists of natural streams of the Danube River in length of 137.5 km, Sava River 446 km, Drava River 198.6 km and Kupa River 5 km, Figure 3, (MSTIRC 2019).

The considered ship for the comparison of two different power system designs from a carbon footprint viewpoint is a diesel engine-powered river cruise ship, with main particulars given below:

Length overall: 109.9 m
Breadth: 11.4 m
Design speed: 12 kn

The vessel named MS Prinzessin Sisi, Figure 4, is equipped with two Caterpillar main engines with 783 kW each. More data on the vessel can be found in (CM 2019) and (Ship particulars 2019). The vessel can transport 156 passengers and it was built in 2000 and refurbished in 2015.

Even though MS Prinzessin Sisi does not formally belong to Croatian inland fleet, it navigates on

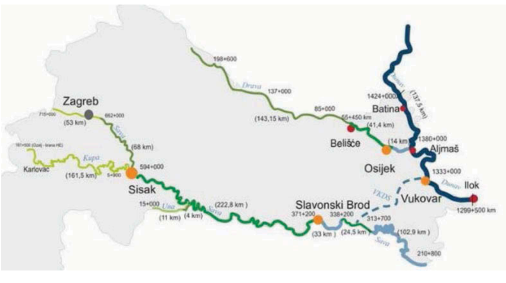

Figure 3. Inland waterway network of Croatia (MSTIRC 2019).

Figure 4. Analyzed river cruise ship in operation (CM 2019).

Danube River through Croatian area, on its way to the Black Sea. The design speed is 12 knots, but the average speed that ship achieves is 7.8 knots (MT 2019). Since the ship power is roughly proportional to the cube of its speed, average ship power on that route was calculated according to the following expression:

$$P_{average} = P_1 \cdot \left(\frac{v_{average}}{v_1}\right)^3 \quad (1)$$

The calculated average power is 430 kW. Taking into account the average speed, the energy consumption is estimated at 55.1 kWh/nm. The fuel consumption of the ship has been calculated by multiplying energy consumption with specific fuel consumption (SFC). SFC is determined depending on the engine speed, as proposed by Ančić et al. (2018b), i.e. it is assumed that for high speed engines with engine load of 25%, the SFC yields 240 g/kWh, which is used in this assessment. The fuel consumption of this ship is then calculated and equals 13.2 kg/nm.

3 LCA OF DIESEL ENGINE-POWERED SHIP

3.1 *Crude oil recovery*

Production of domestic crude oil in Croatia is performed on exploitation fields in the continental part of the country. In addition to domestic production, Croatia also imports crude oil primarily from Azerbaijan, Iraq and Kazakhstan (CERA 2016). Due to the lack of data specific for Croatia on process of crude oil recovery, for this assessment, inputs, outputs and process parameters have been used from GREET 2018 database (process Conventional Crude Recovery).

3.2 *Transportation of crude oil*

It is assumed that the crude oil has been transported from Middle East via tankers and pipelines to Croatia. After tankers deliver crude oil to the offshore terminal in Omišalj on the island of Krk, it is then further transported through the oil pipeline system up to oil refineries in Rijeka and Sisak. For this

Table 1. Tailpipe emissions from inland passenger ship.

Emission	Emission factor	Tailpipe emission
	g emission/kg diesel	
CO_2	3206	43.32 kg CO_2/nm
CH_4	0.019	0.25 g CH_4/nm
N_2O	0.142	1.87 g N_2O/nm

assessment, due to reason of simplicity, it is assumed that diesel is produced only in refinery Rijeka. Length of oil pipeline from offshore terminal to this refinery equals 7 km (CERA 2016).

3.3 *Production of diesel*

After the transportation, crude oil is refined in the refinery in order to produce diesel fuel. It is assumed that diesel fuel used by MS Prinzessin Sisi corresponds to Conventional Diesel from GREET 2018 database. Therefore, for the process of diesel refining, the parameters are obtained from GREET 2018 default process of refining conventional diesel.

3.4 *Transportation of diesel*

After diesel is produced, it is mostly distributed by tank trucks to the gas stations. Mode parameters are obtained from default GREET 2018 mode for heavy-duty truck. Tank trucks transport diesel 450 km to the gas station.

3.5 *Vessel operation*

Previously determined ship energy need is 55.1 kWh/nm, while consumption of diesel is 13.2 kg/nm. Tailpipe emissions from diesel combustion in internal combustion engine have been calculated by multiplying ship fuel consumption by emission factors, as prescribed in (EPA 2019), Table 1.

4 LCA OF BATTERY-POWERED SHIP

4.1 *Electricity generation, transmission and distribution*

Electricity generation is the process of generating electric power from sources of primary energy. The main types of energy sources are shown in the Figure 5 with the exception of nuclear energy which production does not exist on the territory of Croatia (HEP 2019).

A more detailed breakdown of individual energy sources is provided in the Figure 6 (HEP 2019).

The electricity generation data are obtained from GREET 2018 database (Non distributed U.S. Mix). Processes of electricity generation by water, wind and solar energy are assumed to be emissions-free since these processes do not require other products

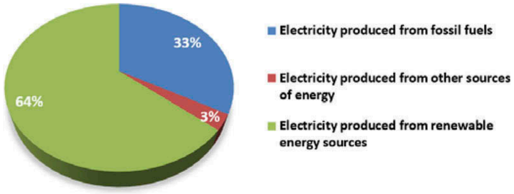

Figure 5. Shares of individual energy sources in total produced electricity in Croatia.

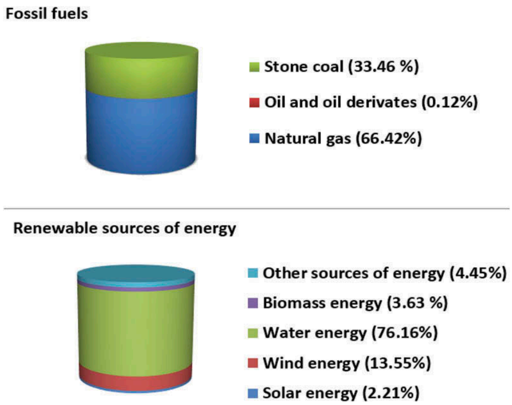

Figure 6. Energy sources for electricity generation in Croatia divided on fossil fuels and renewable energy sources.

for the generation process and the emissions released by building up the generation facilities are not included into the system boundary. Shares of total electricity generation were adapted to the case study of Croatia. After its generation, electricity has been transmitted and distributed to consumers.

4.2 *Vessel operation*

Battery-powered ship is supplied with a power by the on-board battery only. It is assumed that the ship has two propellers powered by two electric motors and that the propulsion power system needs remain unchanged. Due to the losses in the electric motor and the electric power distribution, the required power supplied by the battery is increased by 10% and equals 473 kW, which is the total power output of the battery. Taking into account that the average speed of the ship is 7.8 knots, the energy consumption is 60.6 kWh/nm.

4.3 *Battery*

Environmental regulations, battery innovations and increase in fuel prices open the path to electrification of passenger ships in Europe. Leader in this area is Norway, with introduction of the first fully electric ferry using Li-ion batteries in 2014 (Gagatsi et al. 2016). Even though Li-ion batteries are quite expensive, they have by far the highest energy density compared to other types of batteries. Lead acid batteries appear to be more economical solution. However, the low material resistance in the marine environment and the short life period makes them more expensive in the life cycle of a ship (Dedes et al. 2012).

The considered ship, MS Prinzessin Sisi, navigates through Croatia on Danube river waterway that is 74.2 nautical miles long. The battery is charging on the state border of Croatia, i.e. the ship sails around 9.5h without recharging the battery. The minimum required capacity is around 4500 kWh. Due to safety component, this value is increased by one third of minimum required capacity and equals 6000 kWh. Typical power density of Li-ion battery is around 0.254 kWh per kg. Knowing this data, the weight of battery was easily calculated, and it is around 23.6 tons. The emissions from the process of Li-ion battery manufacturing are obtained from GREET 2018.

5 RESULTS AND DISCUSSION

In order to evaluate the environmental impact of two different ship power systems configurations for the same river cruise ship, LCAs are performed in which GHG emissions have been expressed in CO_2-eq per nautical mile.

The existing diesel engine-powered river cruise ship through its life cycle emits 46.63 kg CO_2-eq/nm. The main share in total GHG emissions has the ship operation with 42.88 kg CO_2-eq/nm, while the WTP GHG emissions are 3.75 kg CO_2-eq/nm, as presented in the Figure 7. WTP GHG emissions from diesel fuel are presented in Figure 8, where the process of diesel refining contributes the most to the release of GHG emissions.

Option of electrification of the existing river cruise ship that navigates through Croatian inland waterways has been explored by taking into account results from LCA of battery-powered ship. During the operation, the battery-powered ship has zero emission but during the production of battery, different emissions are released and considered for the total amount of GHG emissions during WTW

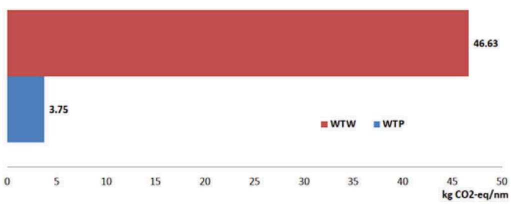

Figure 7. WTW and WTP GHG emissions of diesel engine-powered river cruise ship.

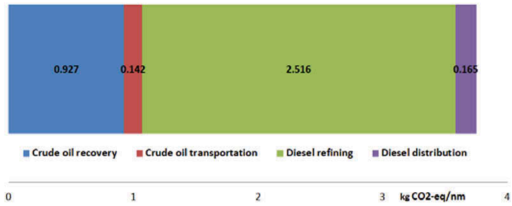

Figure 8. WTP GHG emissions from diesel fuel.

assessment. Results in the Figure 9 represent the WTP GHG emissions from electricity life cycle.

Processes that contribute the most to the GHG emissions are electricity generation from natural gas and coal.

The amount of WTP GHG emissions from electricity is 13.12 kg CO_2-eq/nm. During Li-ion battery manufacturing, certain emissions are released and they equal to 7.27 kg CO_2-eq/nm. WTW GHG emissions from battery-powered river cruise ship are presented in Figure 10, and they contain the emissions from WTP life cycle of electricity and emissions from battery manufacturing. Total WTW GHG emission of battery-powered ship amount 20.39 kg CO_2-eq/nm.

The comparison of LCA results of battery and diesel engine-powered river cruise ship is presented in the Figure 11. As can be seen, the diesel engine-powered ship release significantly higher amount of GHG emissions through its life cycle then the battery-powered option.

During its operation, diesel engine-powered river cruise ship emits 42.88 kg CO_2-eq/nm, while emissions from life cycle of diesel fuel, without its use in ship, amounts to 3.75 kg CO_2-eq/nm. Considering that battery-powered river cruise ship during its whole life cycle emits 20.39 kg CO_2-eq/nm, it can

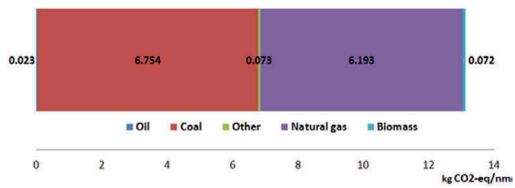

Figure 9. WTP GHG emissions from electricity generation.

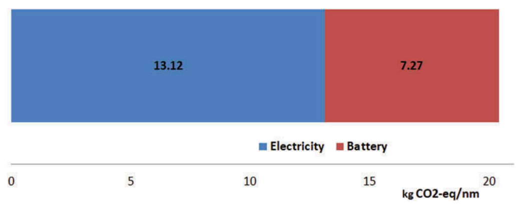

Figure 10. WTW GHG emissions of battery-powered ship.

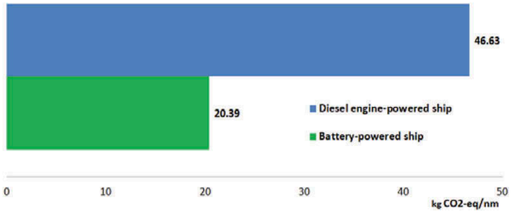

Figure 11. WTW GHG emissions from ship with different power system designs.

be concluded that electrification would significantly reduce environmental footprint of this ship.

Even though the ship is applying slow steaming with average speed of only 7.8 knots, further actions need to be taken in order to reduce GHGs release in the atmosphere. Electrification of the existing diesel engine-powered ship has its benefits due to lower GHG emissions, but it requires higher investment cost, but also the maintenance cost, which refers to the cost of battery replacement after approximately 10 years of its use. Even though the lifetime of a battery is lower than the lifetime of a diesel engine, leading to higher maintenance costs, due to the future more stringent regulation on inland waterways pollution and introduction of carbon pricing policy, electrification seems to be a viable solution that can achieve the decarbonization of the shipping industry.

6 CONCLUSIONS

In order to evaluate the electrification of the river cruise ship, which operates in Croatian inland waterways, from the environmental point of view, LCAs of diesel engine-powered ship and battery-powered ship were performed by means of GREET 2018 software. The analysis is focused on the emissions released through the WTW of the power system configuration. While the LCA of diesel engine-powered ship constitutes of the process of crude oil recovery and transportation to the refinery, diesel refining and its transportation to the pump and finally its use in the ship which results in tailpipe emissions, the LCA of the battery-powered ship comprises of the processes of electricity generation and its distribution, but also of the manufacturing process of the Li-ion battery that is installed on-board as the main power source. The obtained results show that WTW emissions of diesel engine-powered ship are much higher and amount 46.63 kg CO_2-eq/nm, than those released from WTW life cycle of battery-powered ship yielding to 20.39 kg CO_2-eq/nm. Since electrified ship with implemented Li-ion battery releases no gases during its operation and has more than twice lower amount of WTW GHG emissions than the existing ship powered by diesel engine, it can be concluded that electrification is great solution for decarbonization of the shipping industry and compliance with strict regulation on environmental protection. On the other hand, it is fair to say that complete insight into the feasibility of the electrification of river cruise ship will be achieved by comparing the existing and the battery power system also from the economic viewpoint, which will be subject of further studies.

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