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Comparative Life Cycle Assessment of Battery- And Diesel Engine-Driven Ro-Ro Passenger Vessel

Abstract

Emissions produced by the fuel combustion in marine engines are one of major causes of the marine environment pollution and have negative impact on both human health and the environment. That impact is more pronounced for vessels which mostly operate near ports and inhabited areas, such as ro-ro passenger ships. In order to evaluate the environmental impact of a ship, a life cycle assessment of a ro-ro passenger vessel operating in the Adriatic Sea has been performed. Two different power system designs were investigated, i.e. lithium-ion battery-driven vessel and diesel engine-driven vessel. The analyses were performed by means of general LCA software GREET 2018, where the life cycle for both power system designs is divided in two stages: constitutive parts of the first stage are processes from life cycle of fuel without its use in vessel, while vessel operation represents the second stage. The analysis showed that diesel engine-driven vessel emits 79.740 kg CO_2-eq/nm, versus battery-driven vessel with 27.471 kg CO_2-eq/nm.

Keywords: LCA; Electric Ship; Diesel engine; Ship power system; Greenhouse effect

1. Introduction

The Earth's climate is affected by human activities and a continuous flow of energy from the Sun. This energy passes down through the atmosphere to warm the Earth's surface. Greenhouse gases (GHGs) in the atmosphere are blocking infrared radiation from escaping from the surface to space which is known as the greenhouse effect [1]. As a result of that, the Earth's surface is warming up (global warming problem) causing various climate change. Human activities are raising the level of GHGs in the atmosphere. These anthropogenic (man-made) GHG emissions refer to emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases, and they are one of major air pollutants. In order to control these anthropogenic GHGs, some regulations for reduction of GHGs, as the Kyoto Protocol, are introduced [2]. Most recent climate agreement is the Paris Agreement, adopted in 2015, with central aim to keep a global temperature rise this century well below 2 °C above pre-industrial levels and to limit the temperature increase even further to 1.5 °C [3].

With the increase in the energy consumption, the depletion of fossil fuels, high energy costs and atmospheric pollution have become important economic, environmental and social concerns. Marine exhaust gases due to combustion of fuel in engines can be considered as one of the major causes of marine environmental pollution. The most pernicious emissions released from the engines are carbon monoxide (CO), carbon dioxide (CO_2), sulphur oxides (SO_X), nitrogen oxides (NO_X) and particulate matter (PM). The presence of these gases affects the environment and human health with respiratory diseases especially when ships are operating in the port area near inhabited cities. Latest most relevant data on pollutant emissions from maritime sector is the one reported by International Maritime Organization (IMO) in Third IMO GHG Study [4] from 2014: international shipping emitted 796 million tons of CO_2 in 2012, which accounts about 2.2% of the total emission volume for that year. Mid-range forecasted scenarios presented in this study showed that by 2050, CO_2 emission from international shipping could grow by between 50% and 250%. In order to preserve the planet, some actions need to be done in a sense of reduction of these harmful gases.

Air pollution from ships originates from the combustion of heavy fuel oil (HFO) for power generation. However, this fuel is mostly used because it is relatively cheap. In order to comply with strict regulations on energy efficiency and environmental eligibility, HFO need to be changed with some alternative fuel, or conventional ship power system should be replaced by hybrid power system (HPS) or integrated power system (IPS). Nowadays electrification of ships represent very important and attractive research topic in a sense of reduction of pollutant emissions. Kalikatzarakis et al. [5] analysed 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. [6] proposed an optimal power management method for ship electric power systems comprising integrated full electric propulsion, energy storage and shore power supply facility. Beside general economic aspects inherent to all-electric ships, special problem represent load fluctuations. There are a number of recent works dealing with this issue. Rodrigues et al. [7] investigated impact of electric propulsion on the electric power quality of vessels, particularly addressing a significant increase of non-linear loads in the system, due to variable frequency drives feeding the motor. In their study, Gegatsi et al [8] 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-driven ferries seem to be the most environmental 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 batteries and capacity limitations of the electricity grid [9]. All in all, electrification of a ship would result in releasing zero emissions during its operation. In order to assess the environmental impact of that ship, the emissions released from electricity and battery production are needed to be considered.

Life cycle assessment (LCA) provides a quantification of emissions through whole life cycle of a specific product. This technique is evaluating the environmental impact of a product through its life cycle: from its production, through its use and up to eventual reuse, recycling or disposal [10]. The results of LCA can be presented in amount of different emissions, which are released from processes during its life cycle, and in energy consumption. It also represents an useful tool for comparison of different propulsion system in order to evaluate their impact on the environment. Such kind of research was performed by Jwa et al. [11]. They completed comparative LCA of lithium-ion battery electric bus and diesel bus, from extraction of fuel and generation of energy to vehicle operation. Results showed that vehicle driven by diesel engine has higher emissions than car driven on lithium-ion battery.

The aim of this paper is to perform comparative LCA of battery- and diesel engine-driven ro-ro passenger ship operating in the Adriatic Sea. The Croatian Adriatic coastline is indented and has numerous islands with many ferry lines. Operating near ports and inhabited areas, these ferries have negative effect on the port environment and human health. In order to assess the environmental impact of that ships thorough all phases of life cycle, the LCAs are performed by software GREET 2018.

This paper is structured into seven sections. In the next section the methodology of LCA of the Croatian ro-ro passenger vessel is presented. The third section contains the basics of performing the LCA by means of GREET 2018 software, while the fourth is dedicated to LCA of diesel engine-driven ro-ro passenger ship and LCA of battery-driven ro-ro passenger ship in fifth section. The sixth section contains the results and discussion of performed LCA comparison. Finally, concluding remarks are drawn in seventh section.

2. Methodology

2.1. Life cycle assessment

According to International Organization for Standardization (ISO 14040) [12], LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, by compiling an inventory of relevant inputs and outputs of a product system; evaluating the potential environmental impacts associated with those inputs and outputs; interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study. LCA investigates the environmental aspects and potential impacts throughout a product's life (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. The first assessment is based on data of existing ro-ro passenger ship which is operating on the Croatian side of the Adriatic Sea. The second assessment is a simulation of an electric battery implemented in the existing Croatian ro-ro passenger ship. Processes of raw material recovery, production of fuel and fuel supply to the vessel are referred as "Well to Pump" (WTP), while WTP processes and use of fuel in vessel operations as "Well to Wheel" (WTW). Figure 1 shows the life cycle of power sources that are used in assessments in this research.

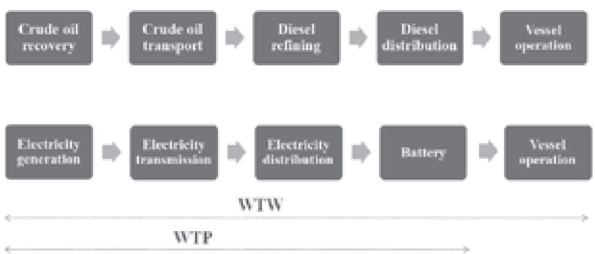

Figure 1: Life cycle of fuels

For LCA of ro-ro passenger ship driven by diesel engine, the assessment begins with an extraction of crude oil. After crude oil is recovered, it is transported to refinery where it is processing into diesel fuel. Diesel is then transported by pumps and ultimately ends up in the ro-ro passenger vessel. Electricity generation followed by electricity transmission, distribution, battery charging and ro-ro passenger ship operation constitute the whole life cycle of power source of electric driven ship. During all of that processes that are mentioned, pollutant emissions like GHGs, NO_X, SO_X etc., are emitted. The comparison of those two different power systems designs is based on the results that are describing total emitted emissions of harmful gases throughout the entire fuel lifecycles described above.

Tailpipe emissions from diesel combustion in marine engine have been calculated by multiplying ship fuel consumption with emission factors, which are presented in Table 1. Typically, GHGs are reported in units of CO_2 equivalent (CO_2-eq). Gases are converted to CO_2-eq by multiplying their global warming potential (GWP) over 100 years, which are presented also in Table 1. GWP was developed for comparison of global warming impacts of different gases. It is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emission of 1 ton of CO_2. The time horizon usually used is 100 years [13].

Table 1: Emission factors and GWPs for GHGs [14]

Emission	Emission factor (g emission/kg diesel)	GWP (100 years)
CO_2	3206	1
CH_4	0.019	25
N_2O	0.142	298

Total amount of emitted GHG emissions for battery- and diesel engine-driven Croatian ro-ro passenger vessel 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 considered ship for the comparison of two different power system designs is a diesel engine-driven ro-ro passenger ship, with main particulars given below:

Length overall:	99.8 m
Length between perpendiculars:	89.1 m
Breadth:	17.5 m
Draught:	2.4 m
Deadweight at max. draught:	950 t
Design speed:	12.5 kn

The vessel is equipped with four Volvo Penta main engines with maximum continuous rating (MCR) 450 kW each. More data on the vessel can be found in [15]. The vessel design speed is 12.5 knots at 80% MCR (1440 KW) of main engines. The vessel can transport 600 passengers in total, 320 in closed space (salon) and 280 on open decks Total vehicle capacity is 145 standard cars.

Figure 2: Analysed ro-ro passenger ship in operation [16]

This ferry is operating on route that connects two parts of Croatia mainland in southern part of the country, port of Ploče and port of Trpanj. The distance between these ports is 8.15 nm and the average duration of one way trip is 60 minutes. Excluding manoeuvrings in ports, it is assumed that ship sails around 50 min, so the effective calculated average speed of ferry on that route is 9.8 knots. 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:

$$P_{average} = P_{80\%MCR} \cdot \left(\frac{v_{average}}{v_{80\%MCR}} \right)^3 \tag{1}$$

The calculated average ship main power is 694 kW. To obtain total power consumption on board, the auxiliary engines' power needs to be added. There are 2 auxiliary diesel generators on board rated at 360 kVA each. It is assumed that they are operating at 50% of MCR. With the power factor assumed to be 0.85, the required electric power for the ship auxiliary system is 308 kW. Assuming the efficiency of electric generator is 95%, total output of these engines is then 324 kW. By summing up the auxiliary engines powers and the main engines powers, the total power of the ship was calculated and equals 1,018 kW. Taking into account the average sailing speed, the energy consumption is estimated at 104 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. [17], i.e. it is assumed for medium speed engines the *SFOC* is 180 g/kWh, while for high speed engines the *SFOC* yields 215 g/kWh, which is used in this assessment. The fuel consumption of this ship on the route Ploče-Trpanj is then calculated and equals 22.36 kg/nm.

3. Software for life cycle assessment

In this paper two LCAs are completed with GREET 2018 model. GREET stands for Greenhouse gases, Regulated Emissions, and Energy use in Transportation and it is a software that was developed at Argonne National Laboratory. This software provides LCA simulations of alternative fuels and vehicle technologies [18]. In Figure 3 the interface of the software is presented.

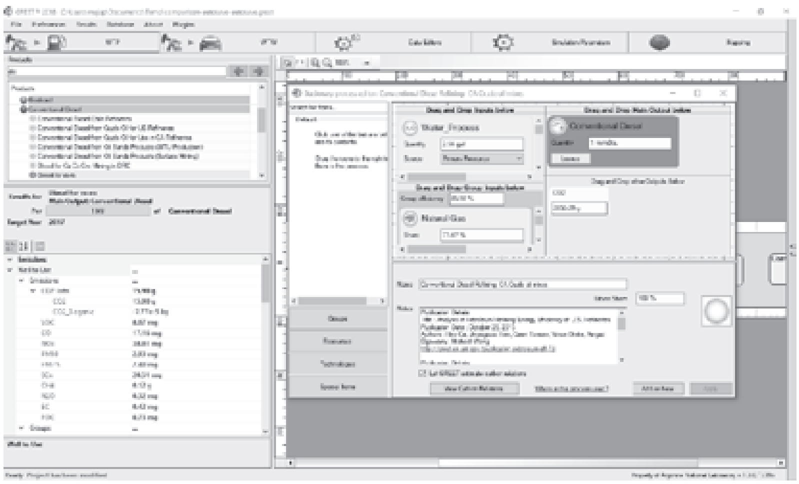

Figure 3: The GREET 2018 interface

In GREET 2018, the WTP and the WTW assessments can be performed. This software contains database of resources, technologies, processes, pathways of products, modes of transport for transportation process, vehicles and emissions. Results of LCA sum up all of the energy and emission associated with the process inputs.

4. Life cycle assessment of diesel engine driven ro-ro passenger vessel

The LCA of diesel engine driven vessel includes processes from raw material (crude oil) preparation, production of diesel in a refinery, to its combustion in marine engine. In all these phases of life cycle, emissions of pollutant gases are released in the atmosphere.

4.1. Crude oil recovery

Crude oil is a raw material which is needed for diesel production. Production of domestic crude oil in Croatia is performed on exploitation fields in the continental part of the country. Domestic crude oil production in 2016 amounted to 684,000 tons. In addition to domestic production, Croatia also imported crude oil primarily from Azerbaijan, Iraq and Kazakhstan, which amounted to 2.53 million tons in 2016 [19]. Due to the unavailability 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).

4.2. Transportation of crude oil

For this assessment, it is assumed that the crude oil has been imported from Middle East and transported 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 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. Centrifugal pumps are powered by the electrical motor to transport the oil from terminal to refinery [19].

4.3. Production of diesel

After the transportation, crude oil is refined in the stationary process in refinery in order to produce diesel fuel. Ro-ro passenger fleet in the Adriatic Sea uses “Eurodiesel Blue” as a fuel. This fuel is a diesel fuel painted blue according to the Regulation on the Implementation of the Excise Duty Act, which pertains to the gas oil painted blue for the use in agriculture, fisheries, aquaculture and sailing [20]. According to the viscosity, it corresponds to Conventional Diesel from GREET 2018 database, therefore, process inputs, outputs and parameters are obtained from GREET 2018 default process of refining conventional diesel (Conventional Diesel Refining-CA Crude oil mixes).

4.4. Transportation of diesel

After diesel is produced, it is mostly distributed by tank trucks to 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 in the port of Ploče.

4.5. Vessel operation

Previously determined ship energy need is 104 kWh/nm, while consumption of diesel is 22.36 kg/nm. In order to calculate the tailpipe emissions generated by combustion of diesel in marine engine, the emission factors are multiplied by consumption of diesel. Tailpipe emissions, expressed in mass of gas released per nautical mile, are presented in Table 2.

Table 2: Tailpipe emissions from ro-ro passenger vessel on route Ploče-Trpanj

Tailpipe emissions	
CO_2	71.69 kg CO_2/nm
CH_4	0.42 g CH_4/nm
N_2O	3.17 g N_2O/nm

5. Life cycle assessment of electric ro-ro passenger ship

In order to comply with stringent regulations on releasing emissions of pollutant gases in the atmosphere, electrification of existing Croatian ro-ro passenger ship, that is propelled by diesel engines, would be of a great significance because those kinds of ship have zero emissions during the operation. In order to quantify all emissions emitted throughout whole life cycle of fuel, LCA for potential battery-driven ro-ro passenger vessel has been performed.

5.1. Electric energy generation, transmission and distribution

For electric ro-ro passenger ship to be driven, electric energy is needed. Electricity generation is the process of generating electric power from sources of primary energy. For the case of Croatia, the electric power generation in 2017 is presented in Figure 4.

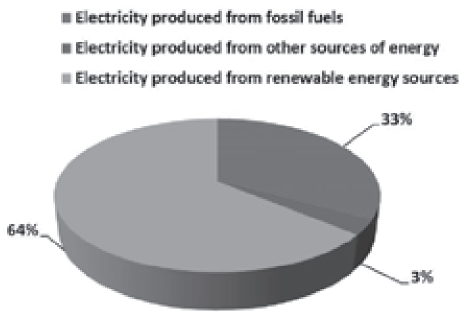

Figure 4: Shares of individual energy sources in total produced electricity in Croatia

Above graph shows the structure of electricity produced on the territory of Croatia. The main types of energy sources are also shown in Figure 4, with the exception of nuclear energy which production does not exist on the territory of Croatia. A more detailed breakdown of individual energy sources is provided on the Figure 5 [21].

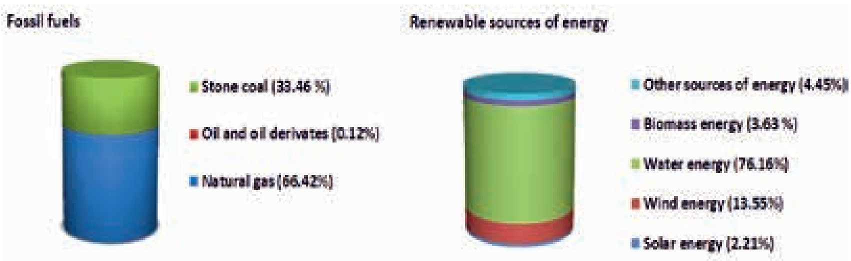

Figure 5: Energy sources for electricity generation in Croatia divided on fossil fuels and renewable sources of energy

The electricity generation data are obtained from GREET 2018 database (Non distributed U.S. Mix), where shares of total electricity production were adapted to the case study of Croatia. After its generation, electric energy has been transmitted and distributed to consumers.

5.2. Battery

Environmental regulations, battery innovations and increase in fuel prices open the path to electrification of ro-ro passenger ships in Europe. Leader in this area is Norway, with introduction of the first fully electric ferry using Lithium-ion (Li-ion) batteries in 2014 [8]. 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 [22]. For this assessment, Li-ion battery is implemented on board. It is assumed that this battery would have to power the ship during 2 trips (from Ploče to Trpanj and back from Trpanj to Ploče), and in this assumption safety component is included. Capacity of the battery is 1800 kWh which is enough for ship to sail and return. 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 7 tons. The emissions from the process of Li-ion battery manufacturing are obtained from GREET 2018. Before the ship sails, the battery needs to be charged for that route. The battery is assumed to be charged in departing port, i.e. Ploče.

5.3. Vessel operations

Battery-driven ship is supplied with power only by the on board battery. The ship power needs are defined in section 2.2. It is assumed that the ship has two propellers driven by two electric motors. Also it is assumed that the propulsion and the auxiliary power system needs to remain unchanged. Due to losses in the electric motor and the electric power distribution, the required power for the propulsion system supplied by the battery is increased by 10 % and equals 759 kW. The electric power for the auxiliary system is 308 KW as determined in section 2.2. The total power output of the battery is 1,067 kW. Taking into account that the average speed of the ship is 9.8 knots, the energy consumption is 109 kWh/nm.

6. Results and discussion

In order to evaluate the environmental impact of two different ship power systems for the same ro-ro passenger vessel, LCAs are performed in which GHG emissions have been expressed in CO_2-eq. The results are presented through WTP and WTW assessments.

According to assessment, the existing diesel engine-driven ship through its life cycle emits 79.74 kg CO_2-eq/nm. The most of it is emitted during its operation on the sea as it can be seen from the Figure 6.

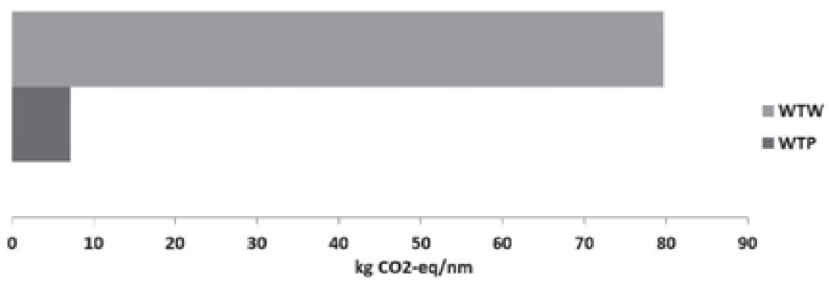

Figure 6: Total emitted emissions from diesel engine-driven ship expressed in kg CO_2-eq/nm.

The main share in total emissions of GHG has the ship operation with 72.64 kg CO_2-eq/nm, while the WTP GHG emissions are 7.10 kg CO_2-eq/nm. WTP GHG emissions from diesel are presented in Figure 7.

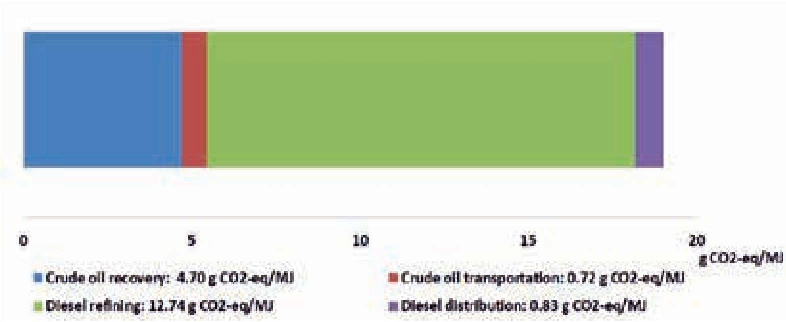

Figure 7: WTP GHG emissions (g CO_2-eq/MJ) from diesel

The total amount of WTP GHG emissions is 18.99 g CO_2-eq per MJ of diesel where the process of diesel refining contributes the most with release of GHG emissions. Electricity that had been used for process of diesel refining and for centrifugal pumps in Croatian crude oil terminal is electricity that has been modified with Croatian shares in generation of electric energy and used in LCA for the battery-driven ro-ro passenger vessel.

Option for electrifying the existing ro-ro passenger ship in the Adriatic Sea has been explored by taking into account results from LCA of battery-driven ship. During its operation, electric ship has zero emission but during the production of battery, different emissions are released and taken into account for total amount of GHG emissions during WTW assessment. Total amount of GHG emissions is 71.309 g CO_2-eq/MJ. Results in the Figure 8 represent the WTP GHG emissions from electricity life cycle. It is assumed that processes of electric power generation by using water, wind and solar energy are emission-free. Processes that contribute the most to the GHG emissions are electricity generation from natural gas and coal.

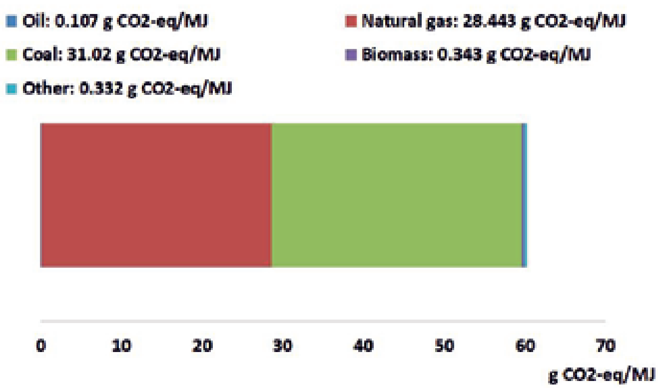

Figure 8: WTP GHG emissions expressed in g CO_2-eq per MJ of electricity

The amount of WTP GHG emissions from electricity is 60.245g CO_2-eq/MJ. During Li-ion battery manufacturing, certain emissions are released and they amount to 11.064 g CO_2-eq/MJ. WTW GHG emissions from battery-driven ro-ro passenger ship are presented in the Figure 9, and they contain the emissions from WTP life cycle of electricity and emissions from battery manufacturing.

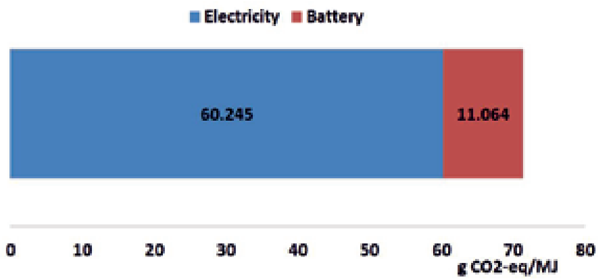

Figure 9: WTW GHG emissions of electric ship

Emissions during total life cycle of a ship propelled by different power system are expressed in kg CO_2-eq/nm. As it can be seen from the Figure 10, emissions from diesel-engine driven ship are significantly higher with 79.740 kg CO_2-eq/nm, versus battery-driven ship which emitted 25.768 kg CO_2-eq/nm, where 23.603 kg CO_2-eq/nm is released from processes of electricity generation, while the rest of 2.165 kg CO_2-eq/nm is emitted during battery manufacturing.

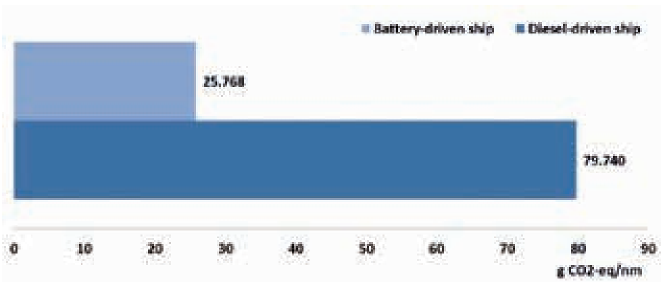

Figure 10: WTW GHG emissions from ship with different power system

During its operation, ship emits 72.64 kg CO_2-eq/nm, while emissions from life cycle of diesel fuel, without its use in ship, amounts to 7.10 kg CO_2-eq/nm. Considering that electric ship during its whole life cycle emits 25.768 kg CO_2-eq/nm, it can be concluded that electrification would significantly reduce environmental footprint of this ship.

Electrification of existing diesel engine-driven ro-ro passenger has its benefits due to lower GHG emissions, but it requires higher investment. In the light of future more stringent regulation on marine environment pollution such solutions seem feasible.

7. Conclusion

In order to evaluate the impact of diesel engine-driven and battery –driven ro-ro passenger ship on the environment, LCAs have been performed by means of GREET 2018 software. The obtained results show that emissions during life cycle of diesel engine-driven ship are much higher with 79.740 kg CO_2-eq/nm, than those released from life cycle of electric ship yielding to 25.768 kg CO_2-eq/nm. By taking all these results into account, it can be concluded that diesel engine-driven ship contributes more to atmosphere pollution. These emissions refer only to emissions released from processes of electricity generation and battery manufacturing because electric ship do not emit emissions during operation. It can be concluded that the electrification of existing ro-ro passenger ship would have high impact on the ship environmental footprint reduction.

It is necessary to mention that the accuracy of the performed LCA can be further improved by analysing every step in the electricity production in more detail. For instance, other refineries (not only Rijeka) and other transportation types in crude oil manipulation can be considered. Also, the ship operational profile can be investigated more thoroughly. However, it is reasonable to expect that irrespective on the scenario, the electric-driven ship will be advantageous from the environmental viewpoint.

On the other hand, it is fair to say that complete insight into the feasibility of the above solutions will be achieved by comparing them also from the economic viewpoint, which will be subject of further studies.

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