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Life-cycle cost assessments of different power system configurations to reduce the carbon footprint in the Croatian short-sea shipping sector

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Abstract

In order to comply with stringent environmental regulations, shipbuilders and ship-owners are seeking cleaner fuels and the integration of renewable energy sources into ship power systems. Such solutions regularly result in additional costs for ship operators, both in the case of retrofitting existing ships or acquiring completely new vessels. This paper deals with the life-cycle cost assessments (LCCAs) of different power system configurations of a ro-ro passenger vessel operating in the Croatian short-sea shipping sector. Electrification of the ship is considered as an option to reduce the carbon footprint (CF) of the vessel and to achieve economic savings during its lifetime. In this sense, the ship operational profile is analysed and its total power needs are determined. The life-cycle assessments of an existing diesel engine-powered solution and two potential battery-powered ship options (with and without photovoltaic cells) are performed by means of GREET 2018 software. Furthermore, these options are compared from an economical viewpoint, where different carbon credit scenarios are investigated. The results show that a diesel engine-powered vessel has the highest carbon footprint, as expected. However, it is also found that a battery-powered vessel (with or without photovoltaic cells) has a minimum environmental footprint and at the same time represents economically the most favourable solution for all possible carbon allowance scenarios. This indicates that all-electric ships seem to be a promising option for the future development of the Croatian short-sea shipping sector.

Keywords: short-sea shipping; LCCA; CO_2 emission; carbon credit; ship power source, all-electric ship.

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Highlights:

- The applicability of different power sources in short-sea shipping is investigated
- LCAs and LCCAs of different power options for ro-ro vessels are performed
- The influence of carbon credit policies in the marine sector is considered
- The electrification of the Croatian ro-ro fleet is a viable option to reduce the CF

Nomenclature

Variables

A	area (m^2)
E_{rad}	annual solar irradiation (MJ/m^2)
P	power (kW)
SFC	specific fuel oil consumption (g/kWh)
t	operational time (h)
v	ship speed (kn)

Greek symbols

η	efficiency (-)

Subscripts

80% MCR	80% maximum continuous rating
ave	Average
PV	photovoltaic system

Abbreviations

CF	Carbon Footprint
CP	Current Policy
GHG	Green-House Gas
GWP	Global Warming Potential
IMO	International Maritime Organization
LCA	Life-Cycle Assessment
LCC	Life-Cycle Cost
LCCA	Life-Cycle Cost Assessment
NP	New Policy
NT	Non-Taxation
PTW	Pump-To-Wheel
PV	Photovoltaic
SD	Sustainable Development
WTP	Well-To-Pump
WTW	Well-To-Wheel

1. Introduction

1.1. Regulatory framework for energy efficiency and the environmental footprint in the shipping sector

Nowadays, ship energy efficiency and the effect of marine transportation on the maritime environment have become very important issues for all parties involved in the shipping sector, i.e. shipbuilders, ship-owners, public authorities, policy makers, etc. Marine exhaust gases from the combustion of fuel in engines can be considered one of the major causes of marine environment pollution. The most pernicious emissions released from internal combustion engines are carbon monoxide (CO), carbon dioxide (CO_2), sulphur oxides (SO_X), nitrogen oxides (NO_X) and particulate matter (PM_{10}). Greenhouse gases (GHGs) in the atmosphere cause the greenhouse effect, which leads to the warming of the Earth's surface and has an impact on various climate changes. These GHG emissions refer to emissions of CO_2, methane (CH_4), nitrous oxide (N_2O) and fluorinated gases [1].

Different regulations, such as the Kyoto Protocol of 1997 [2], have been introduced to control GHG emissions at the global level. The most recent climate agreement is the Paris Agreement, adopted in 2015, with the key aim to keep the global temperature rise this century well below 2 °C above pre-industrial levels and even to limit the temperature increase to 1.5 °C [3].

Carbon footprint (CF) assessment is widely recognized as a relevant approach to quantifying GHG emissions. According to [4], the CF represents a measure of the total amount of CO_2 emissions directly and indirectly caused by an activity or accumulated over the life stages of a product and is regularly expressed in tons of CO_2 or in tons of CO_2 equivalent (CO_2-eq). Nowadays, CF assessment and procedures to reduce the CF are among the research topics that are attracting most interest in almost all types of human activity, such as civil engineering [5], the communication sector [6], agriculture [7], etc. The carbon footprint is regularly assessed as a result of life-cycle analysis (LCA), which provides a quantification of emissions through the whole life cycle of a specific product [8].

Marine transportation offers many advantages and can be considered as the cheapest and the most energy efficient way of transporting large amounts of cargo [9]. According to the International Maritime Organization (IMO), in 2012 global shipping emitted about 1,016 million tons of CO_2 which represents nearly 3.1% of global CO_2 emissions [10]. However, if no actions are taken, these emissions are expected to increase from the 2012 levels by 50-

250% by 2050. In addition, these emissions are highly correlated to fuel consumption, as well as other emissions to air (NO_X, SO_X and PM_{10}). Even though the overall CO_2 emission from the shipping industry is quite low on a global scale, the UN stance is that every industry has to contribute to the reduction of global GHG emissions.

This is recognized by the International Maritime Organization (IMO) which adopted a new regulation on energy efficiency for ships in 2011 [11]. Control of ship engine emissions is regulated by MARPOL Annex VI, [12], which was first adopted in 1997, limiting the main air pollutants contained in exhaust gases, such as SOx and NOx, prohibiting intentional emissions of ozone depleting substances, as well as regulating shipboard incineration and emissions of organic compounds from tankers [13]. MARPOL Annex VI has been revised and amended on many occasions, and nowadays includes two sets of emission and fuel quality requirements: global requirements, and requirements applicable to ships in Emission Control Areas (ECAs), as explained in [13]. Regarding SOx emissions, MARPOL Annex VI prescribes the maximum percentage of sulphur content in marine fuel, where different levels are allowed within ECAs and globally, as listed in [13]. Some other measures to reduce sulphur emissions are also allowed, such as the use of exhaust gas cleaning systems. NOx emission limits are set for diesel engines depending on the engine maximum speed, where we distinguish Tier I, Tier II, and Tier III standards, respectively. The Tier I and Tier II limits are global, while the Tier III standards apply only in NOx ECAs. It should be mentioned that there are no specific particulate matter emission regulations, but their levels are regulated indirectly within fuel standards.

A new regulation introduced in 2011 [11] requires every ship of GT=400 and above engaged in international shipping to have the International Energy Efficiency (IEE) Certificate. In order to obtain it, the ship has to comply with the requirements of the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). The EEDI is a technical measure and requires that for every new ship the Attained EEDI must be calculated and must not exceed the Required EEDI, which is defined by the EEDI reference line value and the appropriate reduction factor X. The reduction factor is defined in a set of time intervals, roughly 10% reduction every 5 years. The EEDI reference line should represent the average ship energy efficiency of the current fleet, whilst the reduction factor should represent a requirement for new ships to improve their energy efficiency compared to the status of the current fleet [14]. The SEEMP must be developed for a ship according to the Guidelines and must be kept on board [11].

Although the EEDI does not fundamentally represent a carbon footprint reduction measure, one should not ignore its origin in the so-called CO_2 Index, also introduced by the MEPC. In spite of renaming it EEDI, it still represents relative CO_2 emissions, i.e. the ratio of CO_2 emissions per ton and nautical mile of cargo transported [15], and, as elaborated by Traut et al. [16], the aim of these requirements is to regulate CO_2 from the shipping industry. Several guidelines have been issued to ensure the smooth and uniform implementation of EEDI and SEEMP, as for instance [17] and [18], but the literature review indicates a number of weaknesses of the current legislation and difficulties in its practical application As elaborated in [9], the current EEDI regulations do not properly consider that the market of container ships has changed radically in the last decade, where the number of ultra-large container vessels has increased. These ships satisfy the EEDI requirements very easily (due to their large capacity and relatively high operating speed) and there is practically no regulation encouraging improvements in their energy efficiency. A very significant drawback of the existing EEDI regulations is the fact that only one operating point, defined by design speed, is considered as relevant [14]. However, in real ship operations, this speed is very seldom achieved. This is particularly the case for ships involved in short-sea shipping, such as ro-ro passenger vessels that change their operating profile frequently. For some ship types like bulk carriers, the EEDI reduction factors are set too rigidly [15]. In its current form, the EEDI regulations are not applicable to complex power systems such as integrated or hybrid ones [19]. Generally, the EEDI is highly sensitive to the ship design speed [20], and, as discussed in [21], the EEDI baseline does not seem to be properly set for some ship types. Finally, there are several gaps in the SEEMP guidelines compared with the international standard for energy management systems [22]. Overall, both the EEDI and the SEEMP requirements will have an impact on the energy efficiency of ships, but one that is not sufficiently high [23].

1.2. Improvements in the ship power system to reduce GHG emissions

The overall goal to improve energy efficiency and to reduce the environmental effect of shipping can be achieved through a set of technical (EEDI-related) and operational (SEEMP-related) measures. In general, the technical measures to reduce the carbon footprint used in the shipping sector are: measures related to the propulsion system, vessel design and vessel equipment, exhaust after treatment, engine internal measures, use of alternative fuel/energy (LNG, electricity, hydrogen, biofuel), while the set of operational measures includes: measures related to speed reduction, smart steaming, journey planning, on-board information systems, and optimal maintenance. In addition, measures related to the organization of the logistical chain, to the interface between inland ships and other transport modes, and to the interface of ships and infrastructure (locks, terminals and seaports, etc.) should also be mentioned.

With the aim to increase the energy efficiency of ships, conventional energy systems (diesel-mechanical propulsion) can be replaced by an alternative hybrid (HPS) or an integrated power system (IPS), with reduced pollutant emissions as a consequence. The HPS is characterized by the use of different types of power sources, while the main characteristic of the IPS is centralized electric power generation and the application of electric propulsion. For example, Ančić et al. [19] proved that ro-ro passenger ships with IPS or HPS are more energy efficient compared to the fleet average which uses mechanical propulsion. Many studies have shown that pollutant emissions can be reduced by using renewable power resources such as the sun and wind for power generation on board. For example, Klebanoff et al. [24] showed how a hybrid high-speed fuel-cell ferry can reduce GHG emissions. Yu et al. [25] presented a hybrid electric power system for sightseeing vessels designed for short sailing, consisting of four-stroke diesel generators, solar panels and Li-ion batteries. CO_2 emissions have been dramatically reduced in hybrid energy systems compared with conventional systems. Another example of HPS implemented on a ship was designed by Diaz-de Baldasano et al. [26] as innovative hybrid diesel electric-fuel cell propulsion. Two high-temperature solid oxide fuel cell (SOFC) systems using methanol as a fuel were integrated on a ship and the result was the reduced emission of GHG. Ahn et al. [27] investigated a marine generator fuel cell-gas turbine hybrid system in terms of energy efficiency and environmental impact in very large ethane carriers. The general conclusion from the above references is that hybrid systems using renewable energy sources and alternative fuels and technologies increase energy efficiency and reduce the environmental footprint of ships. However, costs still remain an issue.

Due to environmental regulations and the depletion of fossil fuels, the electrification of ships represents a very important research topic. Gagatsi et al. [28] presented a fully electrified ferry as a new paradigm in short-sea shipping. So far, typical battery-powered ro-ro passenger ships could use batteries as the main power source on short trips and they could be charged whilst connected to shore power. The great advantage of this kind of ship is that it produces zero emissions during navigation.

1.3. The aim of the paper

From the above literature review, the following research gap is evident: there is no unified approach to the design of a ship power system which should simultaneously comply with energy efficiency and environmental regulations at a reasonable price. The integration of renewable energy sources in the ship power system is a rather case-specific task which should be performed for each vessel separately, simultaneously taking into account its technical characteristics and operating profile (highly dependent on the navigation area).

The aim of this paper is therefore to investigate the applicability of different power system configurations for the reduction of the CF that can be implemented on board a ro-ro passenger ship engaged in short-sea shipping in the Croatian part of the Adriatic Sea. Through the life cycle cost assessment (LCCA) of these power system options, the most environmental and economical solution for retrofitting this kind of ship is highlighted.

The contribution of this study is summarized as follows: (a) the development of a model to calculate the CF of a Croatian ro-ro passenger ship that operates in the Adriatic Sea; (b) the determination of the most economical and ecological power system configuration for retrofitting the same ship.

This paper is structured into five sections. In the next section the LCAs of different power system configurations for Croatian ro-ro passenger ship are elaborated in detail. The third section contains the LCCA of selected energy power systems, while the fourth section is dedicated to a discussion of the performed assessments. Finally, concluding remarks are drawn in the fifth section.

2. The LCA of ship power system configurations

2.1. Theoretical background of LCA

According to the International Organization for Standardization (ISO 14040) [29], LCA is a method to investigate the environmental impacts of a product throughout its life cycle, which includes:

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

In this paper, a number of LCAs are performed by means of GREET 2018 software. Processes of raw material recovery, the production of a power source and its supply to the vessel are referred to as "Well-to-Pump" (WTP), while WTP processes and the use of the power source in vessel operations are termed as "Well-to-Wheel" (WTW), Figure 1. Vehicle operations are referred to as "Pump-to-Wheel", or, in the case of a ship, "Pump-to-Propeller".

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

The results of the performed LCAs are emissions released during the life cycle of power system configurations and are presented in units of CO_2-eq.

2.2. Ship energy needs and particulars

The considered ro-ro passenger ship operates in the Croatian short-sea shipping sector, Figure 2, and its main particulars are:

- 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 a maximum continuous rating (MCR) of 450 kW each. More data on the vessel can be found in [30]. Its design speed is 12.5 knots at 80% MCR (1440 KW), and its loading capacity yields 600 passengers and 145 standard cars. The distance that the ship sails during one round trip is 16.3 nm and the number of round trips per year is 1,740 [31].

Figure 2 Ro-ro passenger ship in operation [32]

This ferry operates on a route connecting two parts of the Croatia mainland in the southern part of the country, i.e. the port of Ploče and the port of Trpanj, with a length of 8.15 nm and an average duration of a one-way trip of 60 minutes. Excluding manoeuvrings in ports, it is assumed that the ship sails for around 50 min, so the effective calculated average speed of the ferry on that route is 9.8 knots. Since the ship power is roughly proportional to the cube of its speed, the average ship power on that route was calculated according to the following expression:

$$P_{ave} = P_{80\%MCR} \cdot \left(\frac{v_{ave}}{v_{80\%MCR}}\right)^3. \quad (1)$$

The calculated average ship main power is 694 kW. To determine the total power requirements, the power for auxiliary purposes needs to be added. There are two auxiliary diesel engines on board rated at 360 kVA each, regularly 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 that the efficiency of the electric generator is 95%, the total output of these engines is then 324 kW. By summing up the auxiliary engines' power and the main engines' power, the total power of the ship was calculated at 1,018 kW. Taking into account the average speed, the energy consumption is estimated at 104 kWh/nm. The fuel consumption of the ship was calculated by multiplying the energy consumption with the specific fuel consumption (SFC). The SFC is determined depending on the engine speed, as proposed by Ančić et al.[20], i.e. for medium speed engines, the SFC is assumed to be 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 Ploče-Trpanj route is then 22.36 kg/nm.

The selected power system configurations for the implementation of the test on a ro-ro passenger vessel are battery and photovoltaic (PV) cells. In order to compare different power options on board, first it is necessary to perform the LCA and cost assessment of the existing ship power system, i.e. the diesel engine.

2.3. The LCA of a diesel engine-powered ship

In order to assess the total GHG emissions released during the life cycle of diesel fuel, the emissions from all processes need to be summed up. These processes include crude oil recovery, the transportation of crude oil, diesel refining, diesel distribution and, finally, the use of diesel on the ship which results in tailpipe emissions, Figure 3. Tailpipe emissions from diesel combustion in a marine engine are calculated by multiplying ship fuel consumption with the emission factors, as prescribed in [33]. In order to evaluate the contribution to the greenhouse effect from each of the GHGs, the global warming potential (GWP) has been developed and represents a measure of how much energy the emissions of one ton of a gas will absorb over a given period of time, relative to the emissions of one ton of CO_2. The time range usually used is 100 years and, typically, GHGs are reported in units of CO_2-eq [34].

The 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 [35]. Some specific data that were missing in the case of Croatia in the process of crude oil recovery were taken from the GREET 2018 database (Conventional Crude Recovery process) for the needs of this investigation. Crude oil is transported to the refinery. It is considered here that the crude oil is imported from the Middle East and transported via tankers and pipelines to Croatia. From the offshore terminal on the island of Krk, crude oil is then transported through the oil pipeline system to the oil refineries. For this assessment, for reasons of simplicity, it is assumed that diesel is produced only in the refinery in Rijeka. The length of the oil pipeline from the offshore terminal to this refinery is 7 km [35]. After transportation, the crude oil is refined in a stationary process. The parameters of the diesel refining process are obtained from the GREET 2018 database.

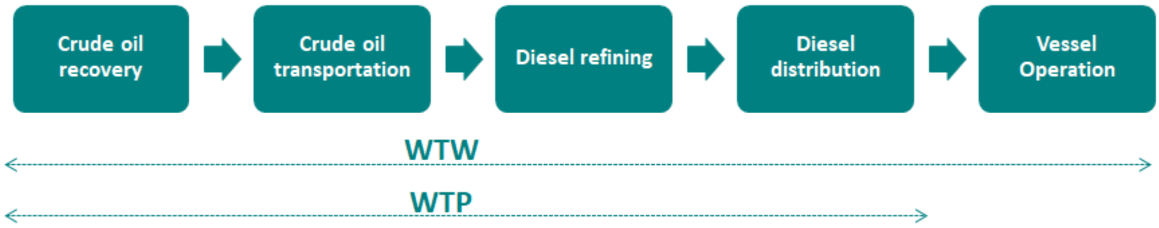

Figure 3 Life cycle of a diesel engine-powered ship configuration

After the diesel is produced, it is distributed by tank trucks to gas stations. Tank trucks transport diesel 450 km to the gas station in the port of Ploče, from where the ship sails towards Trpanj. The previously determined ship energy need is 104 kWh/nm, while the consumption of diesel is 22.36 kg/nm. The calculated tailpipe emissions are presented in Table 1.

Table 1 Calculated tailpipe emissions from the diesel engine-powered ship

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

According to the LCA, the diesel engine-powered ship, through the life cycle of diesel, emits 79.74 kg CO_2-eq/nm. The ship's operation contributes the main share of the total emissions of GHG with 72.64 kg CO_2-eq/nm, while the WTP GHG emissions, Figure 4, are 7.10 kg CO_2-eq/nm. The process of refining diesel contributes the most GHGs. The annual CF related to navigation is 2,060 tons.

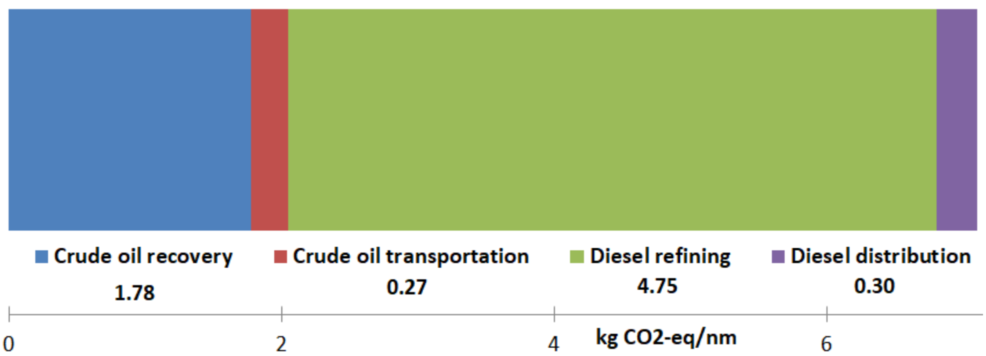

Figure 4 WTP GHG emissions of diesel

2.4. LCA of a battery-powered ship

The second power system configuration represents a Li-ion battery installed on board. Even though Li-ion batteries are quite expensive, they have by far the highest energy density compared to other types of batteries [36], and they are most prominent in shipping applications. The WTP assessment of electricity includes generation, transmission and distribution. The main types of energy sources are shown in Figure 5, with the exception of nuclear energy whose production does not exist on the territory of Croatia. A more detailed breakdown of individual energy sources is provided in Figure 6 [37].

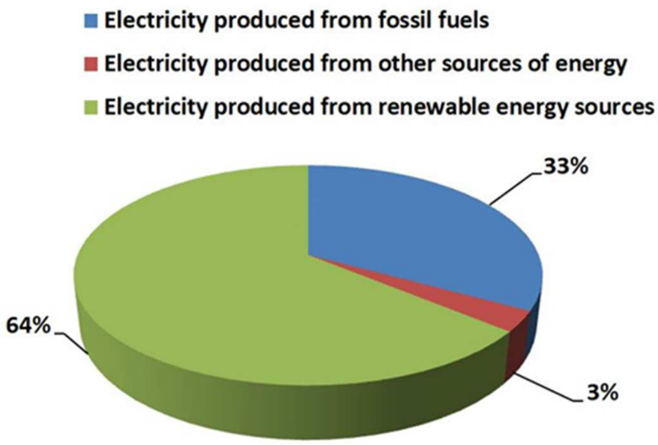

Figure 5 Shares of individual energy sources in total produced electricity in Croatia [37]

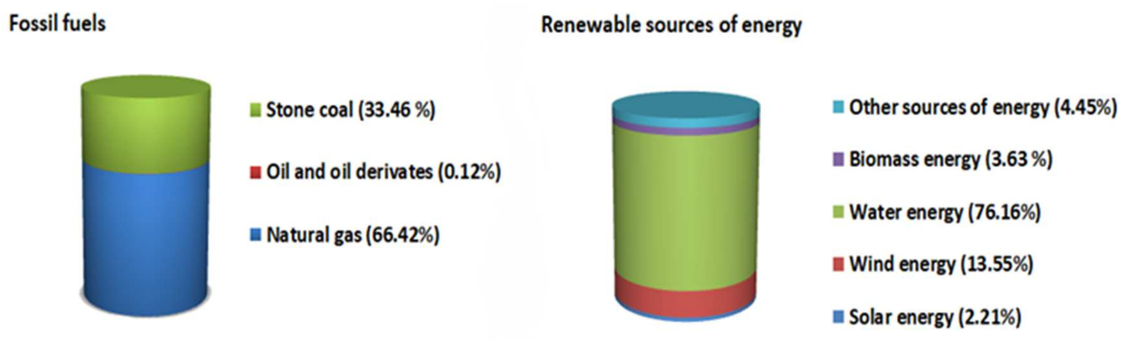

Figure 6 Energy sources for electricity generation in Croatia divided into fossil fuels and renewable sources of energy [37]

The WTP of electricity, the process of battery manufacturing, and ro-ro passenger ship operation constitute the whole life cycle of the power source for a battery-powered ship, Figure 7.

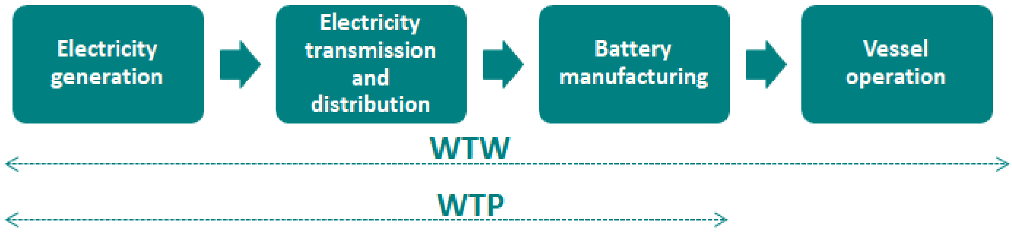

Figure 7 Life cycle of a battery-powered ship configuration

A battery-powered ship is supplied with power by the on-board battery only. The ship power needs are defined in section 2.2. It is assumed that the ship has two propellers driven by two electric motors. It is also assumed that the propulsion and the auxiliary power system needs remain unchanged. Due to the 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. 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.

It is assumed that this battery would have to power the ship during a round trip (from Ploče to Trpanj and back from Trpanj to Ploče). The minimum required capacity is 1780 kWh. Due to the safety margin, this value is doubled and amounts to 3600 kWh. The typical power density of a Li-ion battery is around 0.254 kWh per kg. Knowing these data, the weight of the battery was easily calculated at around 14 tons.

According to the assessment, a battery-powered ship through its life cycle emits 27.92 kg of CO_2-eq/nm. During operation, a battery-powered ship does not have emissions, but during the production of the battery and electricity generation (in the case of Croatia), different emissions are released and taken into account for the total amount of GHG emissions. The results in Figure 8 represent the WTP GHG emissions from the electricity life cycle (23.60 kg CO_2-eq/nm). It is assumed that the processes of electric power generation by using water, wind and solar energy are emission free. The processes that contribute the most to GHG emissions are the generation of electricity from natural gas and coal.

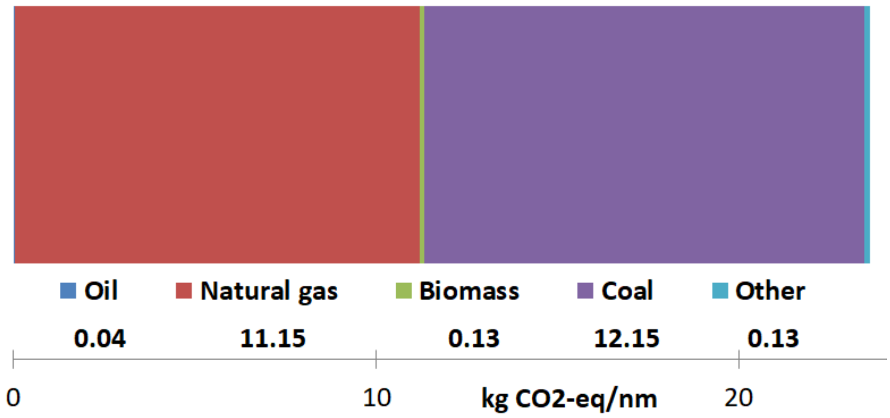

Figure 8 WTP GHG emissions of electricity

Emissions released from the process of battery manufacturing are equal to 4.32 kg CO_2-eq/nm. WTW GHG emissions from a battery-powered ship are presented in Figure 9.

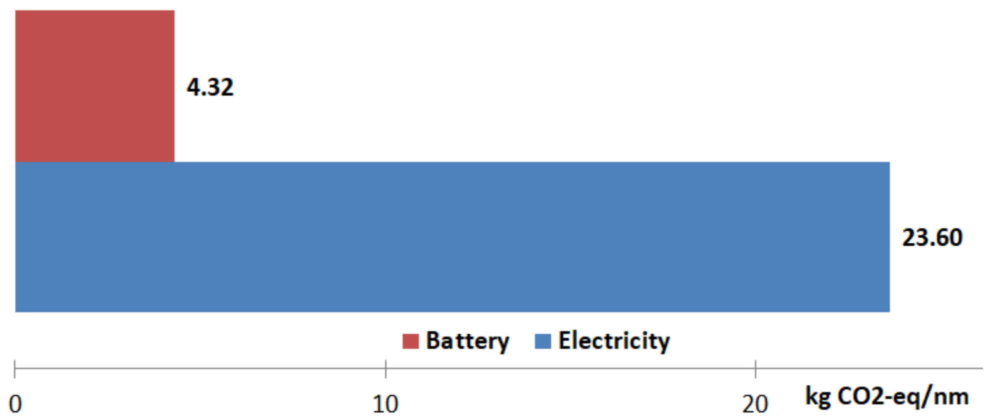

Figure 9 WTW GHG emissions of a battery-powered ship

2.5. PV cells battery-powered ship

The third power system configuration represents the PV cells battery-powered ship, where, on board the previously analysed battery-powered ship, a PV system is installed. A PV system is powered by PV modules, which contain many individual PV cells that are interconnected to form a PV module. For the purpose of a PV system on board a ro-ro passenger ship, an off-grid PV system needs a rechargeable battery such as a Li-ion battery to store electricity for use under conditions where there is little or no output from the PV system, for example on a cloudy day or at night [38]. Usually, the PV cells are placed on the ship top deck so as not to disturb the passengers, the crew and the ship functions. Hence, the total area covered by the PV cells is limited by the ship's main deck dimensions. Since the ship sails in different directions, it is also not possible to align the PV cells directly with the sun. Instead, they are placed horizontally which then reduces the efficiency of the PV cells.

The advantage of PV cells is that they can directly transform solar power into electric power, but their efficiency is relatively low. For this assessment, the data on the efficiency of PV cells (17%) is obtained from a study by Liu et al. [39]. It should also be noted that many PV cell manufacturers provide a warranty for 20 years. Therefore, for this assessment, the life span of PV cells is 20 years.

The LCA of this ship power system configuration takes into account the emissions from the electricity generation process and from the manufacturing processes of the Li-ion battery and the PV module materials, Figure 10.

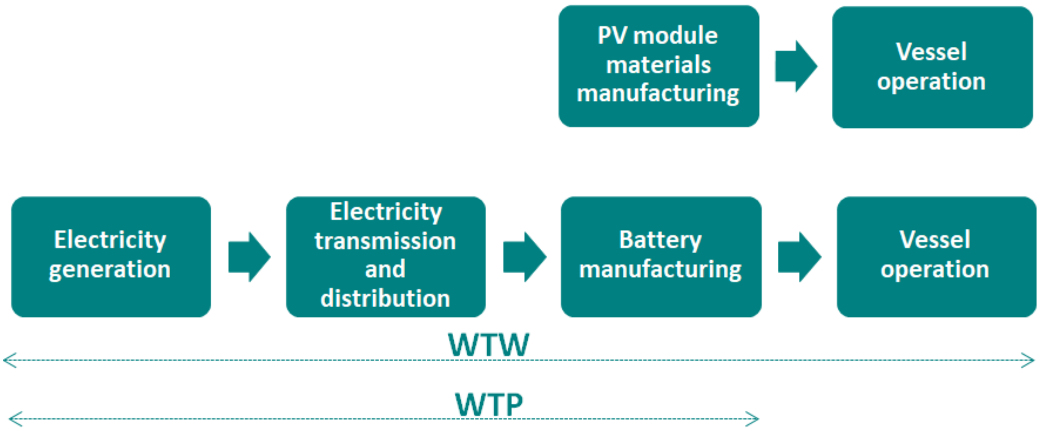

Figure 10 Life cycle of PV cells battery-powered ship configuration

For the area of navigation, the average annual solar irradiance, obtained from the Climate Atlas of Croatia [40], is 5557 MJ/m^2 for horizontally placed cells and 6109 MJ/m^2 for cells aligned at 45°. Since the PV cells are limited to horizontal placement on board, the data for horizontal cells are used. As mentioned previously, the length between perpendiculars is 89.1 m and the ship breadth is 17.5 m. Therefore, the available length for the installation of PV cells is around 60 m, while the available width is 15 m, resulting in the available area estimated at around 900 m^2. The total annual electric energy produced on this route is:

$$E_{PV} = \eta_{PV} \cdot E_{rad} \cdot A = 0.17 \cdot 5557 \cdot 900 = 850.2 \text{ GJ} . \qquad (2)$$

In one year, the ship performs 1,740 round trips. Since the duration of a round trip is 100 minutes, in total the ship sails for 2,900 hours annually. This would amount to an average electric power of:

$$P_{PV} = \frac{E_{PV}}{t} = \frac{850.2 \cdot 10^9}{2,900 \cdot 3600} = 81.4 \text{ kW}. \tag{3}$$

The required power is the same as for the battery-powered ship explained in section 2.4, therefore 1,067 kW, where 81.4 kW is obtained from the PV system and 985.6 kW from the Li-ion battery. The energy consumption of the ship remains the same and amounts to 109 kWh/nm.

Crystalline silicon (c-Si) cells are used due to their low cost, high density and efficiency. They are also more appropriate for use on horizontal surfaces than thin-film PV cells [41]. By weight, c-Si PV panels today contain about 76% glass for the panel surface, 10% polymer (foil), 8% aluminium for the frame, 5% silicon for the PV cells, and 1% copper for the interconnectors [42]. According to some commercial c-Si PV panels [43], the dimension of a module is 1.64 m^2, where the module weight is 19.5 kg and includes about 60 c-Si cells. In order to cover the available area with PV panels (900 m^2), the PV system contains 548 modules with a total weight of 10.7 tons. Since the share of material of c-Si in the PV module is 5%, the weight of the c-Si PV cells is calculated to amount to 534.5 kg. Besides silicon, for this LCA, aluminium, copper and glass are included as material for the PV application, and data on these manufacturing processes are obtained from the GREET 2018 database.

According to the LCA, through its life cycle the PV cells battery-powered ship emits 31.98 kg CO_2-eq/nm. The emissions released from the processes of electricity generation and the manufacturing of the Li-ion battery and the PV module materials are taken into account. The WTW emissions of this ship are presented in Figure 11. The process of electricity generation makes the highest contribution with 21.81 kg CO_2-eq/nm, while the processes of manufacturing the battery and the PV module materials contribute 4.32 kg CO_2-eq/nm and 5.85 kg CO_2-eq/nm.

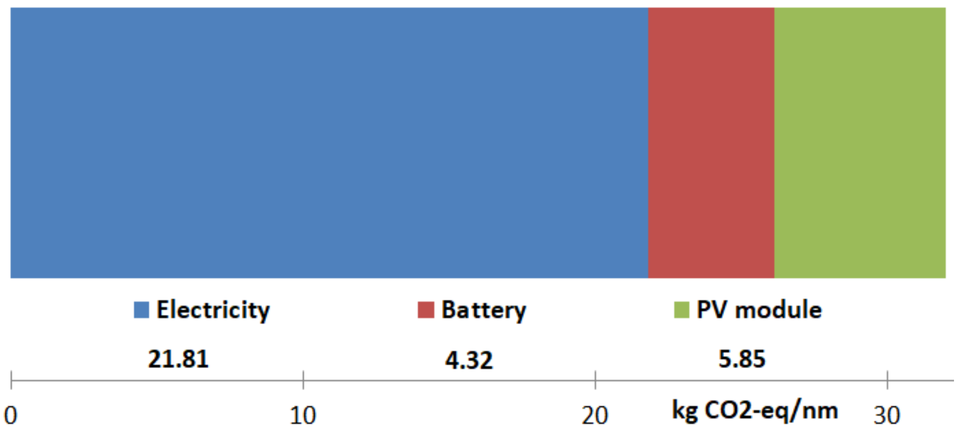

Figure 11 WTW GHG emissions of a PV cells battery-powered ro-ro passenger ship

3. The LCCA of ship power system configurations

3.1. Theoretical background of the performed LCCA

LCCAs of different power system configurations implemented on a ro-ro passenger vessel are performed. The results of the total LCCA refer to costs during the life span of the ship, i.e. 20 years. The total costs of the ship power system configuration include investment (capital) costs and exploitation costs, Figure 12. Maintenance costs, power source costs and carbon credit costs are accounted for in the exploitation costs.

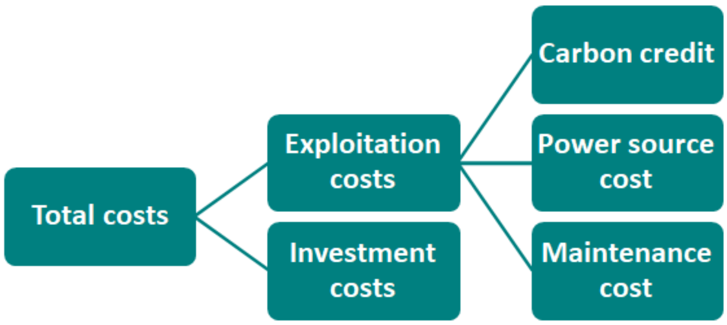

Figure 12 Total costs of a ship power system configuration

Investment costs refer to the additional investment costs of the power system configuration since the diesel engine-powered ro-ro passenger ship already exists, while the maintenance costs refer to the costs of maintenance and replacement of some parts of the power system configuration. Within exploitation costs, carbon credit is also added.

Carbon pricing can play an important role in providing an economically efficient incentive to reduce GHG emissions [44], [45]. Even though carbon pricing has not yet been implemented in the shipping industry, but is the subject of very recent investigations [46], some sectors have already implemented it (industry, aviation, the electric power sector, etc.). Companies receive or buy emission allowances which they can trade with one another as needed. Each allowance gives the holder the right to emit 1 ton of CO_2, the main GHG, or the equivalent amount of two more powerful GHGs, N_2O and perfluorocarbons (PFCs). At the end of each year, a company must hand over enough allowances to cover all its emissions, otherwise heavy fines are imposed. If a company reduces its emissions, it can keep the spare allowances to cover its future needs or else sell them to another company [47].

For the implementation of carbon allowances, known as carbon credit, in the shipping industry, a system to track the emissions of individual ships is required. Recently, the IMO launched the Data Collection System on the fuel consumption of ships. Accordingly, from 2019, ships of GT=5,000 and above are required to collect consumption data for each type of fuel they use. The first report is expected by the end of 2019 [48]. It is reasonable to assume that carbon allowances will also be introduced in the shipping sector in the near future, and therefore it is necessary to consider different carbon credit scenarios in the development of future power system options and ship exploitation strategies, as performed by Trivyza et al. [49] for cruise ship energy systems. They developed a bi-objective optimization method (with life-cycle costs (LCC) and lifetime carbon emissions as objectives) for the synthesis of a cruise ship energy system and applied it to identify optimal power system configurations complying with existing emission regulations. Four scenarios of carbon credit are considered in this study which include the non-taxation scenario (NT) and three carbon pricing policy scenarios (CP, NP and SD). The three CP, NP and SD scenarios were obtained by interpolating the forecast values of the CO_2 price from the World Energy Outlook 2018 [50], Figure 13. These values relate to the industrial, aviation and electric power sectors of the European Union for 2025 and 2040, and are presented in Table 2. In this paper, carbon credit refers to emissions expressed in CO_2-eq. For 2019, the price of CO_2 is zero, since carbon credit has still not been implemented in the shipping industry. The considered scenarios are as follows:

- No tax (NT) scenario: carbon credit will not be implemented and there is no cost for CO_2 emissions;

- Current policies (CP) scenario: considering the current policies that have been implemented in the energy sector;
- New policies (NP) scenario: includes existing policies and incorporates the ambitions of policy makers in the energy sector;
- Sustainable development (SD) scenario: involves policy scenarios to comply with the United Nations 2030 agenda for Sustainable Development. In this scenario, the CO_2 price rises to €125/ton.

Table 2 Forecast of CO_2 prices for the European Union [50]

Scenario	**Price of 1 ton of CO_2 (€)**	
	2025	2040
Current Policies (CP) scenario	20	34
New policies (NP) scenario	22	38
Sustainable Development (SD) Scenario	56	125

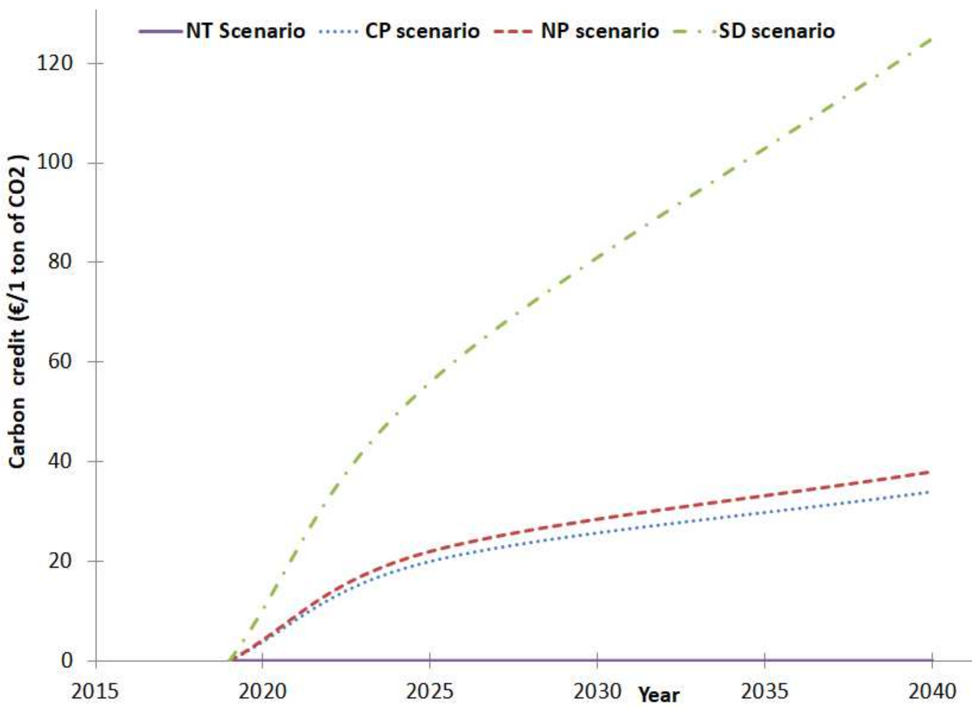

Figure 13 Carbon pricing policies adopted from [50]

Since carbon credit refers to allowances as a permit to emit GHGs during the operation of a ship, these four scenarios are illustrated only using the example of a diesel engine-powered ship.

3.2. Diesel engine-powered ship

The additional investment cost for this ship is not taken into account, since the ship is already built and the scope of this paper is limited to retrofitting options for the existing ship. The cost of diesel for shipping purposes is reduced by the excise duty amount. Accordingly, the price of one litre of diesel is €0.66/L [51]. Taking into account the density of diesel fuel, the ship fuel consumption, the distance of the round trip and the number of round trips per year, the annual costs of fuel are €498,300.

According to Banawan et al. [52], the total annual maintenance cost of a 24 MW diesel engine power plant is $1,195,600. Since the analysed ship has a total installed power of 2,448 kW, the estimated annual maintenance cost of this ship is $122,000, i.e. €108,600.

The cost of carbon credit is added to the total costs. According to the scenarios on carbon pricing mentioned in section 3.1 and data on the annual CF of this ship (2.06 kilo tons of CO_2-eq), the carbon credit costs are presented in Table 3 and in Figure 14.

Table 3 Cost of carbon credit during the lifetime of the ship according to four scenarios

NT	CP	NP	SD
€0	€884,800	€957,900	€2,749,300

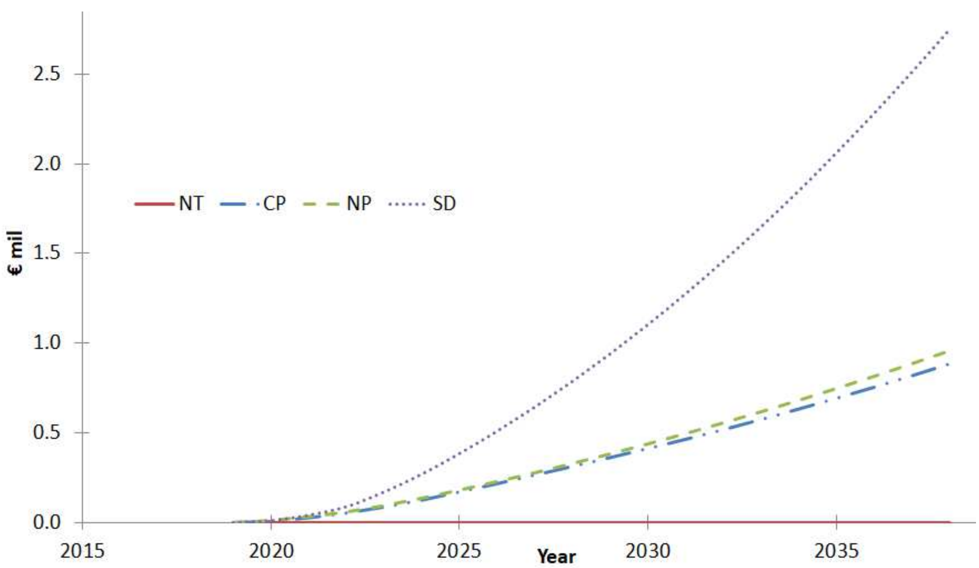

Figure 14 The cost of carbon credit through the entire life span of the ship

3.3. Battery-powered ship

The total price for electricity in the Croatian industrial sector amounts to €78/MWh [51]. Based on the data on ship energy consumption and on the price of electricity, the annual cost of electricity is calculated at €241,200.

One of the obstacles that postpone the large-scale deployment of batteries, and especially of Li-ion batteries, is their high investment cost. The observed costs of battery packs for electrical vehicles based on BNEF (Bloomberg NEF) have decreased from about €870/kWh in 2010 to € 70-215/kWh in 2017. The lower end of the cost range of 2017 coincides with the announcements of market leaders, like Tesla, at about €170/kWh [53]. In this assessment, the battery price used is €200/kWh. Since the required battery capacity is 3,600 kWh, the price of a Li-ion battery is €720,000. As for future Li-ion battery cost scenarios, they are presented in Figure 15, such as in [53].

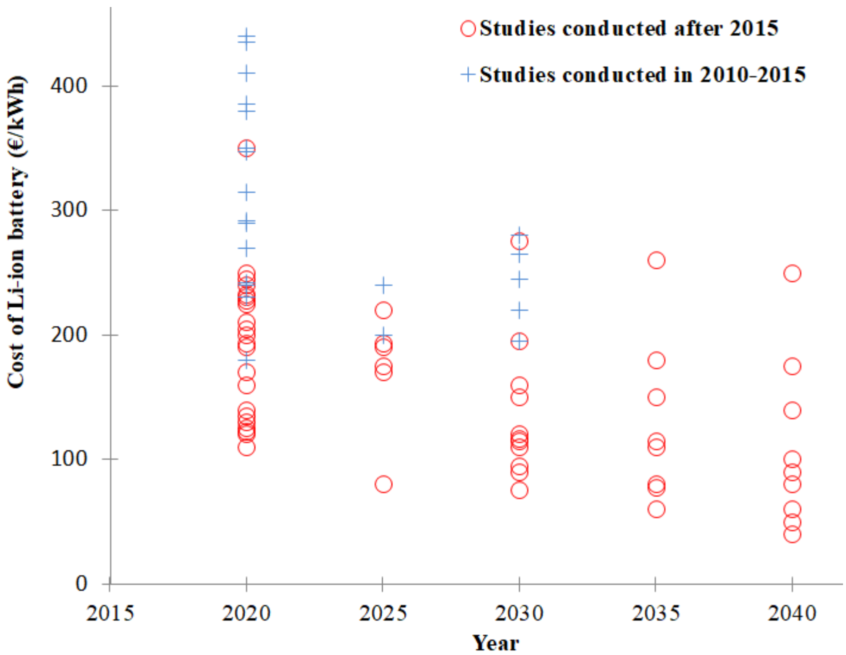

Figure 15 Cost forecasts of a Li-ion battery for electric vehicles

The range of estimates is wide, with values reported from above €400/kWh in the short term to as low as €40/kWh in the long term, and depends on when the study was conducted, as can be seen from Figure 15. The average price estimates, which are used in this paper, are presented in Table 4.

Table 4 Average Li-ion battery price estimates

Year	Cost of Li-ion battery (€/kWh)
2020	244
2025	184
2030	169
2035	129
2040	109

Christos [54] estimated the investment cost to retrofit a double-ended ro-ro passenger ferry into a battery-powered one is €2.2 mil. Roughly 45% of this cost is associated with the battery cost, while the rest refers to electric motors, converters and regulators. In this assessment, the 3,600 kWh battery investment cost is estimated at €878,400. The total additional investment cost would then be around €1,952,000.

The battery is maintenance free, but has a shorter lifetime than the ship. The lifetime of a Li-ion battery is assumed to be 10 years, since many manufacturers provide a warranty for 8 years [53]. Hence, the battery will need to be replaced once in the ship lifetime. The replacement cost is calculated based on the average cost of a Li-ion battery in 2030 which amounts to €169/kWh (Table 4), i.e. the cost of battery replacement would be €608,400.

3.4. PV cells battery-powered ship

The investment and maintenance costs of a Li-ion battery are the same as in the previous subsection, but the electric power consumption is lower. According to section 2.5, 92.37% of the electric power needs are obtained from the Li-ion battery and 7.63% from the PV cells. Therefore, the annual cost of electricity for this option is €222,600.

PV cell costs are continuing to decline, making them more applicable and attractive in areas with excellent solar resources. According to the World Energy Outlook 2018 [50] for the European Union, the investment cost of a PV system in 2017 amounted to $1,300/kW. By considering new policies, this study presents a scenario with PV costs of $760/kW for 2040. The annual maintenance cost is assumed to be 20% of capital costs, i.e. $260/kW. Therefore, the investment costs are calculated at €94,500 and annual maintenance costs amount to €18,900. The maintenance costs of PV cells on board are quite high due to exposure to a salty atmosphere which can trigger corrosion if the PV cells are not protected properly.

4. Discussion

4.1. LCA comparison

In order to evaluate the environmental impact of three different ship power systems as options for retrofitting Croatian ro-ro passenger ships, LCAs were performed. Emissions released during the life cycle of ship power system configurations are presented in Figure 16.

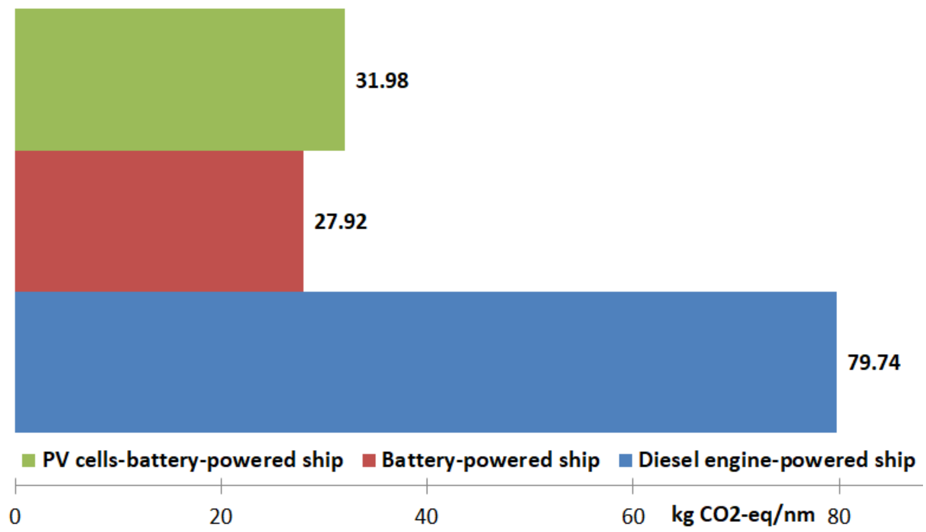

Figure 16 WTW GHG emissions of ships with different power systems

The LCA results show that during its operation, a diesel engine-powered ship emits 72.64 kg CO_2-eq/nm, while emissions from the life cycle of diesel fuel, without its use in a ship, amounts to 7.10 kg CO_2-eq/nm. Considering that a battery-powered ship during its whole life cycle emits 27.92 kg CO_2-eq/nm, it can be confirmed that electrification would significantly reduce the CF of this ship. The third option with PV cells emits a slightly higher amount of GHGs than a battery-powered ship (31.98 kg CO_2-eq/nm). A complete insight into the feasibility of the above solutions is achieved by comparing them also from the economic viewpoint, which is presented in the following section.

4.2. LCCA comparison

The LCCAs of different power system configurations that can be implemented on board are performed. The costs are summarized in Table 5 and in Figure 17. As for the carbon credit cost, two scenarios are taken into account: the NT scenario that matches today's situation in shipping, and the SD scenario which is very rigorous although its inclusion in shipping regulations would lead to a significant reduction in the CF from the maritime industry. The NT scenario is a non-tax scenario, and therefore the carbon credit cost is €0, while the LCC of the SD scenario is €2,749,300.

Table 5 Costs of different power options during the ship's lifetime, expressed in euros (€)

Power system options	Additional investment cost	Power source cost	Maintenance cost	Total costs (NT)	Total costs (SD)
Diesel engine	0	9,966,000	2,172,000	12,138,000	14,887,300
Battery	1,952,000	4,824,000	608,400	7,384,400	7,384,400
PV cells-battery	2,046,500	4,452,000	986,400	7,484,900	7,484,900

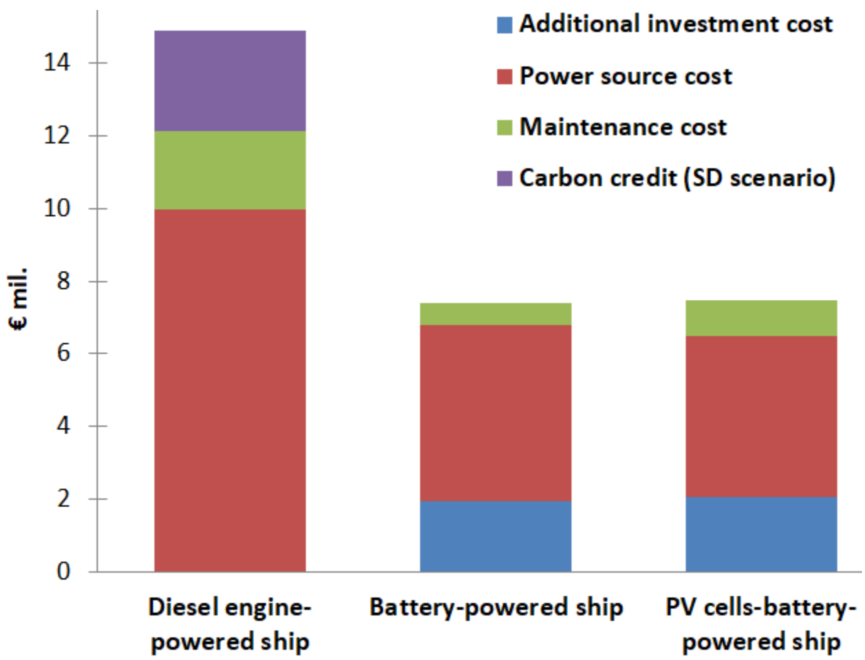

Figure 17 LCCA comparisons of different power system configurations

The diesel engine-powered ship has the highest LCCs (€12,138,000). When the carbon credit cost is added to this amount, the LCCs rise to €14,887,300. Considering that this ship has almost twice the LCCs compared to the other two configurations, and a comparison of the LCAs yields the result that the CF is also by far the highest among the considered configurations, the retrofitting of the existing ship is of great significance. The payback time of the investment cost for a battery-powered ship is 4 years, while for that of a PV cells battery-powered ship it is 5 years.

The results show that electrification of the Croatian short-sea shipping sector seems to be a promising option to reduce its carbon footprint and at the same time to offer significant savings to the ship-owner during the ship exploitation period. Since the majority of ferries in the Adriatic Sea operate on relatively short routes similar to the one observed, the main findings of this study could be applied to them as well. It is expected that for longer routes the battery capacity should be increased, which would lead to a significant increase in the battery system price and possibly render the battery option unfeasible.

Considering installation of the PV system on other ships, the main difference lies in solar irradiation. In this sense, every route should be viewed separately. Since these differences are rather minor for the Adriatic Sea, it can be stated that application of the PV system in the Croatian ro-ro passenger fleet reduces the environmental impact, but does not increase the cost-effectiveness significantly.

There are some limitations of this study with respect to the input data. Namely, relevant calculations are performed for prices in the Croatian energy sector for 2017, and it is not fully clear whether or not the relation between fuel oil prices and electricity production prices will remain the same for the total ship calculation period. This will, of course, affect the payback time for investment in alternative power system configurations. Higher accuracy would be achieved if the direct measurement results of ship power needs were available. Another limitation of this study is that it does not consider the effect of the electrification of the complete Croatian short-sea shipping fleet on the national electric grid loading.

5. Conclusion

In order to evaluate the environmental impact of different power system configurations for the retrofit of a Croatian ro-ro passenger ship, a comparative cost and life cycle analysis of relevant power system configurations was performed. Apart from the diesel engine which is used in the existing vessel, the applicability of a Li-ion battery and PV cells was considered. The main findings of the performed research are summarized as follows:

- emissions during the life cycle of a diesel engine-powered ship are much higher at 79.74 kg CO_2-eq/nm than from a battery-powered ship yielding 27.92 kg CO_2-eq/nm and from a battery-powered ship with PV cells installed on board at 31.98 kg CO_2-eq/nm;
- during the lifetime of a ship, a diesel engine-powered ship has the highest total costs of €12,138,000 in contrast to a battery-powered ship with costs of €7,384,400 and a PV- cell-battery-powered ship with costs of €7,484,900;
- if carbon credit as a potential carbon reduction policy is included in the assessment, the total cost for the diesel engine-powered ship would increase to €14,887,300.

It can be concluded that from the environmental and economical point of view, the best option for retrofitting the existing ro-ro passenger ship is the implementation of a Li-ion battery on board. The payback time of the investment is 4 years. This is a very important finding which can serve as a guideline both for shipyards and ship-owners in the design and acquisition of new ships, respectively. With a reduction of the investment costs for batteries and PV cells, and an increase in the carbon credit cost, these options are expected to be even more appealing to ship-owners in future.

Based on the findings of this study, and taking into account its limitations, as well as the decarbonization trends in the marine sector, it is reasonable to expect that the Croatian shipping sector should move to power systems based on renewables, where, in some intermediate period, hybrid power system options would be preferable. In this sense, a special task should be the proper sizing of each power source in HPS which is influenced by the total power needs of the ship. In addition, consideration should be given to the availability of a particular source and its effect on the safety of the power system.

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