# Life-cycle assessment and life-cycle cost assessment of power batteries for all-electric vessels for short-sea navigation

**Perčić, Maja; Frković, Lovro; Pukšec, Tomislav; Ćosić, Boris; Li, Oi Lun; Vladimir, Nikola**

*Source / Izvornik:* **Energy, 2022, 251**

**Journal article, Accepted version**
**Rad u časopisu, Završna verzija rukopisa prihvaćena za objavljivanje (postprint)**

https://doi.org/10.1016/j.energy.2022.123895

# Life-cycle assessment and life-cycle cost assessment of power batteries for all-electric vessels for short-sea navigation

Maja Perčić[1], Lovro Frković[2,*], Tomislav Pukšec[1], Boris Ćosić[1,2], Oi Lun Li[3], Nikola Vladimir[1]

[1]University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, 10002 Zagreb, Croatia

[2]Center of Technology Transfer LLC, Ivana Lučića 5, 10002 Zagreb, Croatia

[3]Pusan National University, 30 Jangjeon-dong, Geumjeong-gu, Busan 609-735, Republic of Korea

## Abstract

Environmental regulations are gradually striving to decarbonize short-sea navigation fostering the replacement of the conventional power systems with alternative ones. The electrification of ships has been proposed in the literature as a pathway to zero-emission shipping. Among various alternatives, batteries could ensure full conformity with the tightening emission restrictions. However, appropriate batteries for short-sea navigation need to be investigated, since each battery technology has its own environmental impacts and characteristics such as energy density, number of battery cycles, cost, fast charging ability and safety. The aim of this research is to compare the conventional power system with a diesel engine and alternative power system with a selected battery to identify convenient technology for zero-emission shipping according to the environmental and economic criteria. The Life-Cycle Assessment (LCA) and the Life-Cycle Cost Assessment (LCCA) are performed to analyze environmental and economic performance of different powering options. The analysis included ro-ro passenger ships from the Croatian short-sea navigation, highlighting the electrification by a Lithium-ion battery as the most appropriate alternative according to environmental and economic indicators.

**Keywords:** Emission control; Short-sea shipping; All-electric ship; Battery technology; LCA; LCCA

Word Count: 6752

* Corresponding author.
E-mail address: lovro.frkovic@fsb.hr
Telephone number: +385996855466
Postal address: Center of technology transfer llc, Ivana Lučića 5, 10000 Zagreb, Croatia

**Nomenclature**

**Abbreviations**

| | |
|---|---|
| BPES | Battery-Powered Electric Ship |
| D-H | Diesel-powered ship with high *EmEx* scenario |
| D-L | Diesel-powered ship with low *EmEx* scenario |
| D-M | Diesel-powered ship with moderate *EmEx* scenario |
| E-Li | Electrification with a Li-ion battery |
| E-Ni | Electrification with a Ni-MH battery |
| E-Pb | Electrification with a Pb-acid battery |
| GHG | Greenhouse Gas |
| IMO | International Maritime Organization |
| LCA | Life-Cycle Assessment |
| LCCA | Life-Cycle Cost Assessment |
| LFP | Lithium Iron Phosphate |
| Li-ion | Lithium-ion |
| LTO | Lithium Titanate Oxide |
| NCM | Nickel Cobalt Manganese |
| Ni-MH | Nickel-Metal Hydride |
| Pb-acid | Lead-acid |
| PTW | Pump-to-Wake |
| VRLA | Valve Regulated Lead-Acid |
| WTP | Well-to-Pump |

**Variables**

| | |
|---|---|
| *BC* | Battery capacity (kWh) |
| *CapEx* | Capital expenses (€) |
| *EC* | Energy consumption (kWh/nm) |
| *EF* | Emission factor (kg emission/kg fuel) |
| *EmEx* | Emission expenses (€) |
| *IRR* | Internal rate of return (%) |
| *l* | Length of a one-way trip (nm) |
| *LM* | Lifetime mileage (nm) |
| *LT* | Lifetime (year) |
| *N* | Number or return trips (-) |
| *NPV* | Net present value (€) |
| *OpEx* | Operational expenses (€) |
| *P* | Power (kW) |
| *r* | Discount rate (%) |
| *ROI* | Return of investment (%) |
| *SFC* | Specific fuel consumption (kg/kWh) |
| *TE* | Tailpipe emission (kg/nm) |

**Subscripts**

| | |
|---|---|
| *A* | Annual |
| *AE* | Auxiliary engine |
| *ave* | Average |
| *B* | Battery-powered ship |
| *D* | Diesel-powered ship |
| *de* | Design |

# 1. Introduction

Maritime transport is the backbone of the global economy involving more than 90% of the global trade [1]. However, this mode of transport is becoming a major contributor to air pollution [2] and global warming [3], since ships with conventional power systems continue to ensure transport and connectivity. The effort of the Paris Agreement to limit the global temperature increase to 1.5°C above pre-industrial levels puts increasing pressure on reducing Greenhouse Gas (GHG) emissions [4]. The International Maritime Organization (IMO) reported that GHG emissions of the total shipping industry increased from 977 million tons in 2012 to 1,076 million tons in 2018 [5]. To prevent further increase, the IMO released strategy for international shipping to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 levels [6]. Emission Control Areas (ECAs), where the $SO_X$ and $NO_X$ control requirements are stricter than elsewhere [7], support the IMO's strategy to reduce environmental impacts by restricting emissions of air pollutants since approximately 15% of nitrogen oxides ($NO_x$) and 13% of sulphur oxides ($SO_x$) of globally anthropogenic emissions originate from the shipping industry [8]. However, global trends indicate that if diesel engines are retained, absolute amounts of GHGs and other air pollutants would increase from 150% to 250% in the decades ahead [9]. Therefore, the conventional power systems with internal combustion engines need to be replaced with cleaner alternative solutions, such as ship electrification with battery, i.e. Battery-Powered Electric Ships (BPESs) [10].

## 1.1. State of-the-art in ship electrification with batteries

The electrification of ships represents an actual and important research topic, where some researchers focus on the optimization of the electric ship power system [11] and the energy management of such system [12], while others mainly investigate the benefits of electric propulsion. Nuchturee et al. [13] investigated the electric propulsion for ships and indicated that batteries, due to higher energy density, reliability, and lower capital costs are superior to other storages such as supercapacitors and flywheels. With respect to the use of an onboard battery, there are three different types of electrified ships: plug-in hybrid ships, hybrid ships, and all-electric ships [14]. On one hand, both the plug-in hybrid and hybrid ships combine a traditional diesel engine and a battery. Hybrid ship's battery is charged with excess energy from the engine and used to absorb load fluctuations [15], while plug-in hybrid ship's battery is charged by electrical grid and used fully for particular actions such as maneuvering in ports [16]. On the other hand, an all-electric ship uses only a battery as a power source, charges by connecting to the electrical grid and eliminates exhaust gases released during the ship's operation [17]. Electric propulsion is suitable for cruise ships, ferries, icebreakers, drillships, and similar ships [18][19]. Ritari et al. [20] investigated a ferry, which power system consisted of diesel engines and a battery primarily used for power supply in a case of emergency maneuvering, and indicated higher efficiency of auxiliary engines, resulting in reduced maintenance costs and increased lifetime of those engines. Lindstad et al. [21] investigated an offshore supporting ship powered by diesel engines and a battery and concluded that the implementation of a battery results in reduced local emissions. Balsamo et al. [22] analyzed an electric water-bus that operates in the Venetian lagoon and uses the combination of a battery and a supercapacitor. Gagatsi et al. [17] performed the sustainability analysis of the all-electric ferry to show that the main obstacles for wider electrification of the shipping sector, besides investment costs, refer to the battery's energy density. The world's first battery-powered ferry Norwegian MF Ampere in 2015 [23] opened the pathway towards electrification with power batteries.

Research into the use of batteries has rapidly improved their characteristics over the past decade [24]. A selection criteria of appropriate battery for short-sea navigation is based on the energy density and power density, since batteries need to ensure sailing on relatively longer distances as well as managing necessary acceleration [13]. However, other battery characteristics such as lifetime, number of battery cycles, operating temperature range, efficiency and cost also affect ship's sustainability and need to be investigated [25]. One of the most important characteristics is the number of battery cycles, i.e. the number of complete discharge and complete charge cycles that a battery can provide before losing performance or until failure. The key factors that affect the total number of battery cycles are time, number of completed charge-discharge cycles and Depth of Discharge (DoD) [26]. Analogously, this battery characteristic strongly depends on operating conditions and consequently impacts the cost and performance of BPESs. The characteristics of selected battery technologies, i.e. lead-acid (Pb-acid), nickel-metal hydride (Ni-MH) and lithium-ion (Li-ion), are compared in Table 1.

Table 1. Characteristics of selected battery technologies

| **Technology** | **Pb-acid** | **Ni-MH** | **Li-ion** |
|---|---|---|---|
| **Energy density** [Wh/L] | 50-110 [27][28] | 140-420 [28][29] | 200-700 [27][28] |
| **Specific Energy** [Wh/kg] | 20-40 [30][31] | 40-80 [28][30] | 75-250 [13][27][28][30][31][32][33] |
| **Specific Power** [W/kg] | 75-300 [13][27][31] | 300-333 [31][34] | 200-2000 [13][27][31][32] |
| **Lifetime** [years] | 5–15 [27] | 10-15 [31] | 5–15 [27] |
| **Number of battery cycles** | 400-1,000 [13][27][30][35] | 500-2,000 [30][31] | 400-9,000 [30][31] |
| **Operating temperature range** [°C] | -20 to +75 [28][36] | -10 to +60 [28][36] | -25 to +60 [28][36] |
| **Efficiency** [%] | 70-90 [13] | 70-90 [37] | 85-90 [13] |
| **Cost** [€/kWh] | 165 [30] | 146 [30]] | 200 [30] |
| **Remarks [38]** | – Modest specific energy and power<br>– Large number of manufacturers worldwide<br>– Reliance on abundant cheap materials<br>– No memory effect<br>– Low self-discharge rate<br>– Short cycle life | – Satisfactory specific energy and power density<br>– Reliance on eco-friendly materials<br>– Relatively fast recharge<br>– Good safety record<br>– High self-discharge rate<br>– Relatively low number of battery cycles<br>– Weak recovery and recycling schemes | – Outstanding High energy and power density<br>– High number of battery cycles<br>– Technological diversity<br>– Intensive global R&D efforts<br>– High cell voltage<br>– High number of battery cycles<br>– Performance sensitive to temperature |

Pb-acid batteries are usually used in internal combustion engine vehicles where they provide a quick pulse of high current for starting, buffer electrical energy in vehicle operation and supply electrical system when the engine is not in operation. Pb-acid batteries are a mature technology with relatively stable performance, low manufacturing cost, high operational safety, high specific power and capacity to sustain large charging or discharging power rates. However, defects occurred during manufacturing, short lifespan, heavy weight and a large volume have constrained the possibility of their application in BPESs [39][40]. Furthermore, main drawbacks of Pb-acid battery are relatively low specific energy, energy density and number of battery cycles (Table 1). Valve Regulated Lead-Acid (VRLA) batteries are well-established and reliable devices convenient for a wide variety of stationary applications. However, further research needs to be directed towards the development of VRLA battery systems for portable power applications such as Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) [41].

Ni-MH batteries have been in continuous development over the years and their characteristics are more convenient for short-sea navigation than Pb-acid batteries, due to higher specific energy, specific power, and number of battery cycles [31]. Ni-MH batteries that use hydrogen storage alloys as the negative electrode are being manufactured in high volumes for portable power application with worldwide production of over 1 billion cells annually. On one hand, such batteries have increased energy density in terms of volume and weight, increased high-rate power capability and increased tolerance to over-discharge [42][43]. On the other hand, the release of hydrogen gas during charging and creation of explosive atmosphere is one of the main disadvantages of this battery technology [29]. Ni-MH batteries have lower charging efficiencies and self-discharge rates up to 12.5% per day at room temperature conditions, which is aggravated when the environment temperature increases [43]. Ni-MH battery's relatively low specific power and high rate of self-discharge were significantly improved by modification of the surface oxide of the metal hydride alloy [29]. Further improvements in terms of energy density, specific power, faster recharge capability and cost are required to meet the energy demand of ships for short-sea navigation.

Li-ion batteries are considered to be state-of-the-art technology for all-electric ships [44]. Compared with Pb-acid and Ni-MH batteries, the Li-ion battery has unmatchable combination of characteristics such as high energy density, high power density, increased number of battery cycles, fast charging ability and decreased self-discharging rate [45][46]. Main parts of the Li-ion battery are cathode, anode, electrolyte and separator. Li-ion battery type is named after its cathode chemistries. Three different cathode chemistries are recognized to be the most promising and applicable for maritime use: Lithium Nickel Manganese Cobalt Oxide (NCM), Lithium Titanate Oxide (LTO), and Lithium Iron Phosphate (LFP). The NCM is considered to have the highest energy density of the three cathode chemistries, wherefore it is a favored choice for ship manufacturers who need the proper mix of energy density and safety [47]. Different properties concerning battery characteristics are established through different shares of elements, whereas Nickel (Ni) and Cobalt (Co) are increasing specific energy, and Manganese (Mn) is stabilizing layered structure [48]. $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ (NMC111) form is considered to be the present market leader, due to increased energy density, advanced stability [49] and safety [50]. Regardless of the mentioned characteristics, all-electric ships need to connect a larger number of Li-ion batteries into an oversized battery pack to manage not only short-sea navigation power requirements, but also to withstand the impact from both the mechanical [51] and thermal [52] unforeseen accidents [53][54]. Due to the fact that $CO_2$ emissions, lifetime and powertrain cost depend on the battery size, all-electric ships with oversized Li-ion battery packs have decreased relative $CO_2$ emissions and decreased effective battery price, -i.e. normalized with respect to a lifetime [55]. The degradation of the Li-ion battery cells, directed by operating temperature and cycling loading of the battery system [56], significantly affects the overall capability of the battery system. Although batteries have developed rapidly over the past decade, the implementation of different batteries for zero-emission shipping should be investigated considering their lifetime emissions, since their substantial amount is released by the electricity generation and contributes to atmospheric pollution [57].

## 1.2. State-of-the-art in life-cycle assessment and life-cycle cost assessment of ship power systems

The Life-Cycle Assessment (LCA) represents a standardized method for evaluation of the environmental performance of a product and considers released emissions through the entire lifetime, i.e. from the raw material extraction, production of a product, product's use, and final disposal or/and recycling [58]. The LCA is used in the maritime industry because the evaluation of the environmental impact includes not only the emissions related to the direct activities of the shipping sector (e.g. fossil fuel combustion in a ship engine required for ship operation, energy consumption for shipbuilding, etc.) but also the total accumulated emissions over the product lifetime [59].

With respect to the IMO's decarbonization strategy, innovative and energy-efficient technologies need to be implemented in the shipping sector in the near future [60]. Therefore, the LCA in the marine sector is aimed to consider the replacement of conventional fossil fuel-based technologies with alternative powering options. Several studies investigated the environmental performance of a ship powered by alternative fuel in comparison to commonly used marine fuel [61][62][63]. Many studies investigated the environmental impact of implementing Renewable Energy Sources (RESs) or other specific technologies onboard [57][64]. Park et al. [65] performed a comparative LCA of different re-liquefaction systems for liquefied natural gas carriers. Jang et al. [66] performed LCAs of different types of $SO_X$ scrubber systems implemented on ro-ro passenger vessels. The environmental impact analysis of the alternative powering options implementation commonly specifies the system boundary at the power system. In this sense, Strazza et al. [67] performed LCA of methanol-fueled fuel cell for auxiliary power needs onboard and highlighted bio-methanol as an important alternative powering option with lower environmental impact than diesel power system configuration. Jeong et al. [68] performed the LCA to evaluate the environmental performance of the battery-powered system and diesel-powered system on a ferry engaged in the Korean coastal service. The results of the study indicated that a battery-powered system could reduce global warming potential by 35.7%, acidification potential by 77.6%, eutrophication potential by 87.8% and photochemical ozone creation potential by 87.8%. However, the environmental impact of electric ships depends on the energy sources used for electricity generation. Another study that presented a comparative LCA of a diesel-powered and a battery-powered ferry was conducted by Galaaen J.S. [69], in which the ferry was investigated under real operational and weather conditions. The LCA results indicated that replacement of the diesel-powered with battery-powered ferries is the environmentally friendly option if prioritising the reduction of GHG, NOx, PM and SOx emission related impacts.

To include the economic component into the evaluation of alternative powering options, Life-Cycle Cost Assessment (LCCA) needs to be performed along with LCA. The combination of the results obtained from these two assessments offers sustainable decision-making support for alternative technology implementation, e.g. alternative fuel in a ship power system [70]. The LCCA investigates the total costs (sum of investment, maintenance and operation costs) during the lifetime of a ship. The study by Wang et al. [71] performed comparative LCCA of low pressure fuel gas supply systems for liquefied natural gas fuelled ships and indicated that life cycle costs strongly depends on ship scale, costs of the liquefied natural gas and ship operation. The study by Jovanović et al. [72] performed a comparison of different powering options for the autonomous ferries and concluded that all-electric ferry is the most environmental and economic option compared to heavy fuel oil, marine diesel oil, liquefied natural gas, methanol and hydrogen. Despite that authors are not engaged in the LCA, their study analysed the tailpipe emissions, together with the economic profit during the ship's lifetime of 20 years by performing the LCCA. The study by Korberg et al. [73] performed the techno-economic assessment to analyse the potential of replacing the marine fossil fuels with alternative powering options on different ship types and indicated that in the case of ferries battery-powered system can be cost-competitive solution.

Wang et al. [74] performed LCA and LCCA and introduced a ship hull maintenance strategy that highlights the renewal of steel every ten years as an optimal solution. Jeong et al. [75] used a combination of LCA and LCCA to evaluate the environmental and economic benefits of the hybrid ferry compared to the diesel-electric and diesel-mechanical ones. The results of the LCA demonstrated that battery application on ferries engaged on short-routes might be a solution towards maritime transport decarbonisation, while the results of the LCCA confirmed the high cost-effectiveness of hybrid systems compared to the diesel-powered ones. The study by Wang et al. [76] performed the LCA and LCCA comparisons of the battery-powered and diesel-powered ferry and confirmed both the environmental and economic benefit of the all-electric ships. The results indicated that a battery-powered ferry decreased life cycle GHGs by 30% and costs by 15% in comparison to the conventional ferry with a diesel engine. Another study by Wang et al. [77] performed the LCA and LCCA to indicate benefits of integrating the PV system for powering a ferry operating on a short-route in the Marmara Sea. The LCA indicated that application of the PV system as a marine powering option for ferries is an environmentally friendly option that can reduce GHG emissions, while the LCCA results showed that it is also an economically acceptable option that can decrease ferry operation costs. A similar study was conducted by Perčić et al. [78], in which the LCA and LCCA comparisons of the electrified ferry (with and without PV cells) and diesel-powered ferry operating in the Adriatic Sea indicated the electrification potential of the short-sea shipping sector. Another study by Perčić et al. [79] includes a comparative LCA and LCCA of eight fuel alternatives on three ferries from the Croatian coastal navigation and highlighted the full electrification with only a battery as the most viable option that satisfies environmental and economic criteria. The largest share of the emissions of a battery-powered vessel refers to those released during electricity generation. Fan et al. [80] investigated power systems of inland ships operating on the Yangtze River, China, and showed that amount of the released emissions depends on the sources used to generate electricity, i.e. electricity mix. The LCA comparison of the battery-powered ship and the diesel-powered ship indicated a quite small difference between released $CO_2$ emissions related to those configurations, while this difference for the case of Croatia is greater [79]. The main reason for that is the use of the Chinese electricity mix, which mainly consists of fossil fuels (around 60%), whereas the Croatian mix constitutes of 46% of RESs and 43% of fossil fuels. The study by Goel et al. [81] deals with the LCA and LCCA comparisons of the existing fuel-powered and a battery-powered system of public commuter ferries operating in the assumed Swedish energy mix based on hydro, wind and nuclear power. The LCA results indicated that a battery-powered ferry is the most environmentally friendly option in terms of global warming, acidification, eutrophication and photo-chemical ozone creation. When compared to the fuel-powered ferry, the LCCA results indicated a battery-powered ferry as the cost-efficient option that could reduce the capital costs, fuel costs, maintenance costs, end-of-life costs and emission costs by almost 70%, due to the Swedish electricity mix enables lower electricity and emission costs. Perčić et al. [82] performed LCA and LCCA of different fuels on different inland ships (tanker, passenger ship and dredger) engaged in the Croatian inland navigation and highlighted full electrification as the most environmentally friendly option for all considered ship types, while for the passenger ship it represented also the most cost-effective option. As larger battery capacities result in higher costs, full electrification of the tanker and the dredger is not found to be a feasible option with existing batteries. However, these studies are limited to Li-ion battery only, without insight into technical, environmental and economic aspects of other batteries available on the market. As there is a wide range of battery types with a variety of energy densities reflective of their material constitution, life-cycle emissions differ from one type to another. Additionally, since each battery type has different lifetime expectancy, capital costs and maintenance costs also vary. Therefore, when investigating the electrification of ships, LCA and LCCA of different batteries should be performed to fairly evaluate their environmental and economic performance.

### 1.3. The aim of the paper and innovative aspects

While there is no silver bullet solution to achieve decarbonization of the short-sea navigation [83], electrical energy storages for ships such as metal-air batteries, secondary batteries, capacitors, super-capacitors and hydrogen-based energy storage systems are being rapidly improved [40][41]. The transition to zero-emission shipping is assisted by different commercially available battery technologies that could solve energy security concerns, pressures to mitigate climate change and increased demand for energy [85]. To design a highly efficient BPESs, it is of foremost importance to select the adequate battery technology closely adapted to the type and the scale of applications [86]. Regardless of the implementation potential that short-sea navigation has, it did not reach the same level of battery integration and reduction in emissions as other industries [87], because daily operating profile with shorter port stays (e.g. 15, 30, 45 minute stops) represents a sizing factor for the battery and the shore charging infrastructure.

The aim of this paper is to identify the battery for short-sea navigation that can expand the use of all-electric ships, considering environmental and economic aspects. Bearing in mind the diversity of alternative technologies, this paper provides a review of selected batteries and their characteristics to detect the most viable solution that can fulfil powering requirements of all-electric ships. Moreover, this paper discusses technological readiness and gaps of different batteries to replace conventional diesel-powered solutions and decrease maritime transport emissions. The electrification of ships is illustrated on three ro-ro passenger ships from the Croatian short-sea shipping fleet. This study identified the most environmentally friendly battery through the LCA and identified the most economically viable battery through the LCCA. The original contribution of this study includes: (a) review of battery-powered ship's application and battery-powered system's integration in the maritime transport; (b) identification and selection of the most promising battery technology between Pb-acid, Ni-MH, and Li-ion that can replace a ship's conventional diesel-powered system; (c) identification of the most economical and ecological battery system implemented onboard a ship.

## 2. Methods

### 2.1. Assessment of energy needs of the ship

The electrification of ships with different batteries is investigated, where LCA is performed considering the life-cycle of an onboard battery system, while the LCCA is performed by taking into account the total costs of that system. The baseline scenario in the assessments refers to the existing diesel-powered ship, which is used as the indicator of whether electrification with a particular battery is a feasible solution to reduce both emissions and costs. At first, the energy needs of the ships used as the test cases are calculated.

The operative speed in most cases differs from the design speed, generally due to following up the operating schedule, adjusting to the weather conditions, etc. Therefore, the average operative speed, $v_{ave}$ (nm/h), for the selected ships is determined as a ratio of the route length, $l$ (nm), and duration of the trip, $t$ (h). Considering the cubic relation of ship speed and power, the average main engine power, $P_{ME,ave}$ (kW) can be determined [79]:

$$P_{ME,ave} = (P_{ME} \cdot 0.8\,) \cdot \left(\frac{v_{ave}}{v_{de}}\right)^3. \tag{1}$$

The average auxiliary engine load, $P_{AE,ave}$ (kW), is assumed to be 50%. Average ship power needs, $P_{ave}$ (kW), are calculated as a sum of main (propulsion) needs, $P_{ME,ave}$ and auxiliary needs, $P_{AE,ave}$. The energy consumption per distance, $EC$ (kWh/nm), is then calculated according to the following equation:

$$EC = \frac{P_{ave}}{v_{ave}}. \tag{2}$$

The combustion of diesel in a ship engine generates the tailpipe emissions, $TE$ (g/nm), which are obtained by multiplying the $EC$, specific fuel consumption, $SFC$ (kg/kWh), and emission factors, $EF$ (g/kg), such as in the equation:

$$TE_i = EC \cdot SFC \cdot EF_i\,, \tag{3}$$

where $i$ refers to the selected emission type, e.g. $CO_2$, $NO_X$, $SO_X$, etc.

## 2.2. Life-cycle assessment

ISO 14040 [58] and ISO 14044 [88] standards provide a framework and guidelines mainly focused on LCA performance. In this paper, the LCA is applied to investigate the environmental impact of the BPESs, compared to the environmental impact of diesel-powered ship. However, the main limitation of the performed comparative assessment is that the system boundary is fixed on the ship power system, and the LCA considers emissions related to the power system and not on the entire ship. The functional unit of this assessment is the amount of emissions over the ship lifetime, which is set at 20 years.

The LCA is performed by GREET 2020 software which includes the database on fuel production, materials, many processes of obtaining a certain product, etc. The emissions released from the investigated life cycle can be divided into three phases. The first one is the

Well-to-Pump (WTP) phase and it considers emissions released from the fuel cycle, which includes processes of raw material extraction (activities related to the procurement of natural resources, i.e. mining non-renewable materials, harvesting the biomass, and transporting raw materials to processing facilities), fuel production and its transportation to the refueling station. The second phase is the Pump-to-Wake (PTW) phase, and it considers the emissions released during the use of fuel for ship operation, i.e. *TE*. The third phase is the manufacturing phase, and it considers emissions released from the manufacturing process of the main elements (battery, engine, etc.) of a power system. Since both investigated power systems have engines (diesel engine or electric engine), they are excluded from the environmental assessments due to the assumption that they contribute to air pollution in the same manner. Therefore, only manufacturing processes of batteries are investigated, and they are determined based on the lifetime mileage, *LM* (nm):

$$LM = LT \cdot N_A \cdot 2 \cdot l, \tag{4}$$

where *LT* refers to the ship lifetime (year), $N_A$ denotes the annual number of round trips and *l* (nm) denotes the length of the one-way trip.

## 2.3. Life-cycle cost assessment

The cost-effectiveness of the ship's electrification is investigated by performing the LCCA, where the total costs during the lifetime of 20 years are considered. These costs are commonly arranged into two groups: capital expenses (*CapEx*) and operational expenses (*OpEx*). While the *CapEx* refers to the investment cost, the *OpEx* includes the fuel cost, maintenance, and equipment replacement cost.

A cost comparison of different power systems can be performed by reducing their total costs to the Net Present Value (*NPV*). The *NPV* of the power system is calculated according to the following equation:

$$NPV = \frac{CapEx}{(1+r)^0} + \frac{OpEx_A}{(1+r)^1} + \cdots + \frac{OpEx_A}{(1+r)^n}, \tag{5}$$

where $OpEx_A$ represents annual *OpEx*, *r* denotes a discount rate and *n* is the number of years, while the assumed discount rate is set at 5%. In order to get insight into the cost-effectiveness of electrification, the Return On Investment (*ROI*) is determined:

$$ROI = \frac{\left(\sum_{i=1}^{n} OpEx_{D.A,i} - OpEx_{B,A.i}\right) - CapEx_B}{CapEx_B}, \tag{6}$$

where both $OpEx_{D,A}$ and $OpEx_{B,A}$ refer to the annual *OpEx* of the diesel-powered vessel and battery-powered vessel, $CapEx_B$ denotes *CapEx* of the battery-powered vessel, while the $n$ refers to the years, i.e. lifetime of a ship power system.

Economic profitability evaluation of possible investments usually considers an Internal Rate of Return (*IRR*), which refers to the discount rate when the *NPV* of a power system is zero. If *IRR* is higher than the default discount rate, the investment is acceptable.

## 3. Case study: The Croatian short-sea shipping fleet

This case study analyses the Croatian coastal shipping, where the ro-ro passenger ships are of main importance. These ships refer to the roll on - roll of ships for the transport of passengers and vehicles that are driven on the ship on their wheels [89]. The ferry is a typical example of a ro-ro passenger ship. Ančić et al. [90] analyzed the Croatian ro-ro passenger fleet and their released $CO_2$ emissions. The study indicated that 44 ro-ro passenger ships operate on the 27 ferry routes where 3 of them are international, and 24 of them are domestic. Among domestic ferry routes, 8 of them are short, 9 of them are medium-long, and 7 of them are long routes. At the end of 2019, the average age of the world's ro-ro passenger fleet was around 21 years [91], while the Croatian coastal fleet was constituted of ships powered by low energy efficient diesel engines with an average age of 29 years [90].

### 3.1. Analysed ships

Three ships operating on relatively short (Ship 1), moderate (Ship 2), and relatively long routes (Ship 3) are considered. Ship 1 operates on the shortest Croatian ferry lines and connects settlements Prizna and Žigljen. Ship 2 operates on the medium-long ferry line which connects settlements Ploče and Trpanj, while Ship 3 operates on the ferry line Split-Vis, Fig. 1, which is the longest ferry line in Croatia.

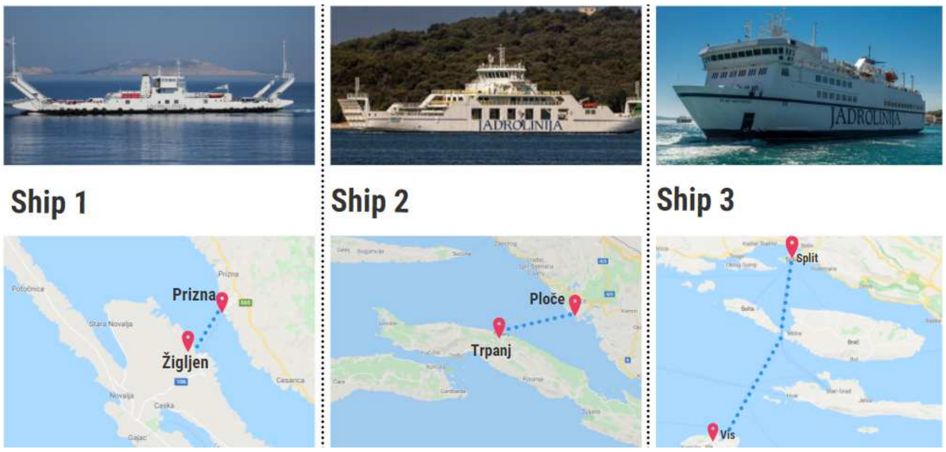


Fig. 1. Analyzed ships and their routes [92]

The ship technical data are taken from [93], while their navigation schedules can be found in [94], Table 2. It is assumed that the common lifetime (*LT*) of a ship power system is 20 years.

Table 2. Technical data of the analysed ships

| | **Ship 1** | **Ship 2** | **Ship 3** |
|---|---|---|---|
| Length between perpendiculars, $L_{pp}$ (m) | 52.4 | 89.1 | 80 |
| Breadth, $B$ (m) | 11.7 | 17.5 | 18.0 |
| Draught, $T$ (m) | 1.63 | 2.40 | 3.80 |
| Power of main engine, $P_{ME}$ (kW) | 792 | 1,764 | 3,600 |
| Power of auxiliary engine, $P_{AE}$ (kW) | 84 | 840 | 1,944 |
| Design speed, $v_{de}$ (kn) | 8.0 | 12.3 | 15.75 |
| Trip duration, $t$ (min) | 15 | 60 | 140 |
| Route length, $l$ (nm) | 1.61 | 8.15 | 30.2 |
| Number of return trips in a year, $N_A$ | 1,590 | 1,740 | 800 |
| Lifetime, $LT$ (years) | 20 | 20 | 20 |

### 3.2. The life-cycle assessment of a diesel-powered ship

The processes included in the LCA of a diesel-powered ship are crude oil recovery, oil transportation to the refinery, production processes, diesel delivery to the refueling station, and finally, diesel combustion in the ship engine, Fig. 2.

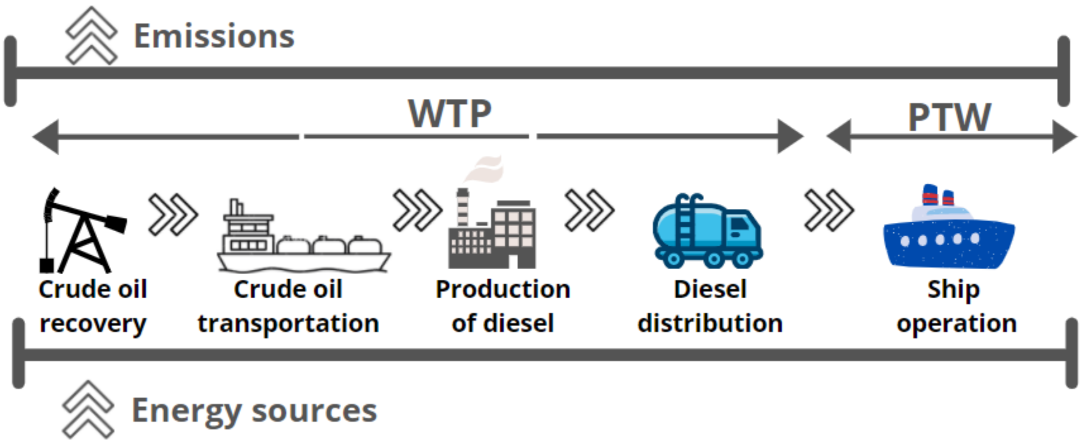


Fig. 2. Schematic presentation of processes in LCA of diesel-powered vessel

The main fuel used in the Croatian navigation is “Eurodiesel Blue” [95]. For the case study of Croatia, it is assumed that the crude oil is only imported from the Middle East and the transportation process starts with the transport from the exploitation site to the port (about 500 km). From there, crude oil is transported via tankers (4,000 km), to the Omišalj terminal (Croatia) and further to the refinery in Rijeka (7 km) by the pipeline. In the refinery, the diesel is produced and it is transported via tank truck to a refuelling station. The distance on which the diesel is transported differs for the investigated ships due to the fact they refuel at the different refuelling stations. Therefore, this trip for Ship 1 yields 100 km, for Ship 2 it is equal to 450 km, and for Ship 3 it yields 350 km. The PTW emissions are calculated according to equation (3), where emissions factors for diesel are obtained from [96], and *SFC* is assumed to be 0.215 kg/kWh [97].

### 3.3. The life-cycle assessment of a battery-powered vessel

Environmental impacts of all-electric ships with different battery technologies are analyzed. The processes included in the analysis are the battery manufacturing process, the process of generating the electricity used for recharging the ship battery, and the ship operation which results in no tailpipe emissions, Fig. 3.

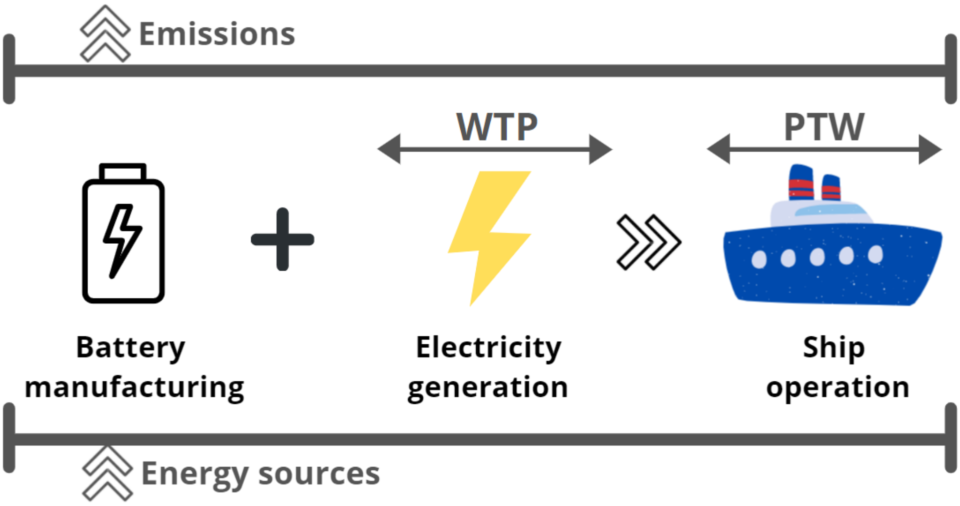

Fig. 3. Schematic presentation of processes in LCA of battery-powered vessel

The battery is the main element of the investigated power system, and its capacity needs to be sufficient enough to ensure the ship operation on a particular route. Due to the great difference between the selected ships' routes, it is reasonable to assume that the battery on Ship 1 and Ship 2 is recharging after a round trip, while the battery onboard Ship 3 is recharging after a one-way trip. Due to gradual battery degradation, which results in the capacity reduction up to 20% of its initial capacity [98], the required battery capacities are increased by 20%. The required capacities are also increased by another 30% (20% due to maintaining the minimum State-of-Charge (SoC) and 10% due to safety reasons). Therefore, the battery capacities, $BC$ (kWh), are increased by 50% in total, and they are obtained from the following equation:

$$BC = 1.5 \cdot EC \cdot 2l, \tag{7}$$

where $l$ (nm) represents the length of the trip in one direction (one-way trip) and $EC$ (kWh/nm) represents the ship energy consumption. The selected batteries are presented in Table 3 together with the main battery characteristics obtained from Table 1. In the performed analysis, the upper limits of the ranges were taken into account.

Table 3. Selected batteries and their data

| Type of a battery | Number of battery cycles | Energy density (Wh/kg) | Cost (€/kWh) |
|---|---|---|---|
| Pb-acid | 1,000 | 40 | 165 |
| Ni-MH | 2,000 | 80 | 146 |
| Li-ion | 9,000 | 250 | 200 |

The environmental footprint of each investigated battery is assessed by the parameters obtained in the GREET 2020 database, where the main input represents the battery weight, and it is obtained by dividing battery capacity (*BC*) with the energy density of a particular battery (Table 3). The emissions of the manufacturing process of the replacement batteries are also considered. Since the battery life is given as the number of battery cycles, and approximately all ships reach an equal number of battery cycles in a lifetime, the batteries are replaced several times (Pb-acid: 32 times, Ni-MH: 16 times, Li-ion: 3 times). As for the Li-ion battery, NMC chemistry is considered for this assessment.

The emissions of the WTP phase refer to the emissions released from the electricity generation process and depend on the share of energy sources used in the mix. In this analysis, the European electricity mix from GREET 2020 database is used, Fig. 4.

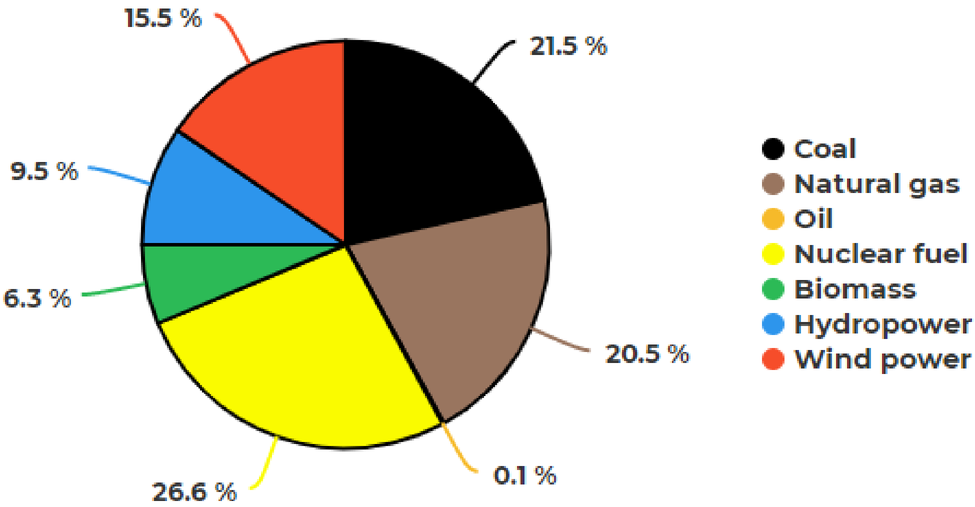


Fig. 4. The European electricity mix

### 3.4. The life-cycle cost assessment of a diesel-powered ship

Even though the existing ship power system has a diesel engine, it has low energy efficiency and needs to be replaced. Therefore, the *CapEx* of a diesel-powered ship refers to the acquisition of a new diesel engine which is calculated by multiplying the average ship power with the assumed conversion factor of 250 €/kW.

The *OpEx* of a diesel-powered ship includes maintenance cost and fuel cost. According to Iannaccone et al. [99], the annual maintenance cost is calculated by multiplying the ship's annual energy consumption with a conversion factor of 0.014 €/kWh. A diesel-powered ship's annual fuel cost is calculated by multiplying the annual energy consumption, specific fuel consumption, and the Croatian diesel price of 0.78 €/kg [100]. The annual *OpEx* are summed, and they are together with *CapEx* inserted in the equation (5) to obtain the *NPV* of the power system.

### 3.5. The life-cycle cost assessment of a battery-powered ship

Around 45% of the *CapEx* of a battery-powered ship refers to the battery price, while the other 55% refers to the costs of additional equipment such as an electric engine etc. [101]. Therefore, the *CapEx* of a BPES can be calculated with the following equation:

$$CapEx = \frac{BP}{0.45}, \tag{8}$$

where *BP* (€/kWh) is a battery price and it is calculated by multiplying the *BC* (kWh) with the costs of a proper battery from Table 3. The maintenance cost of this power system refers only to the replacement of the battery, i.e. *BP*, for a particular number of times during the ship lifetime. The annual electricity cost is calculated by multiplying the annual energy consumption with the Croatian electricity price of 0.078 €/kWh [100].

## 4. Results and discussion

Basic input parameters for the analyzed ships are summarized in Table 4, where the calculated *BC* for each particular ship is also presented.

Table 4. Calculated data for the selected ships

| | **Ship 1** | **Ship 2** | **Ship 3** |
|---|---|---|---|
| Speed, $v_{ave}$ (nm/h) | 6.44 | 8.15 | 12.94 |
| Average main engine(s) power, $P_{ME,ave}$ (kW) | 330.52 | 410.53 | 1,598.24 |
| Average auxiliary engine(s) power, $P_{AE,ave}$ (kW) | 42.00 | 420.00 | 972.00 |
| Total average ship power, $P_{ave}$ (kW) | 372.52 | 830.53 | 2,570.24 |
| Lifetime mileage, *LM* (nm) | 102,396 | 567,240 | 966,400 |
| Energy consumption per distance, *EC* (kWh/nm) | 57.85 | 101.91 | 198.58 |
| Battery capacity, *BC* (kWh) | 280 | 2,490 | 8,990 |

The comparative LCA of different ship power systems is performed, where the life-cycle $CO_2$, $NO_X$ and $SO_X$ emissions are investigated and arranged into three groups of emissions: WTP, PTW and manufacturing emissions. The results are presented in Fig. 5, where D denotes a diesel-powered ship, while the E denotes electrification of a ship with a Li-ion battery (E-Li), Ni-MH battery (E-Ni) and Pb-acid battery (E-Pb).

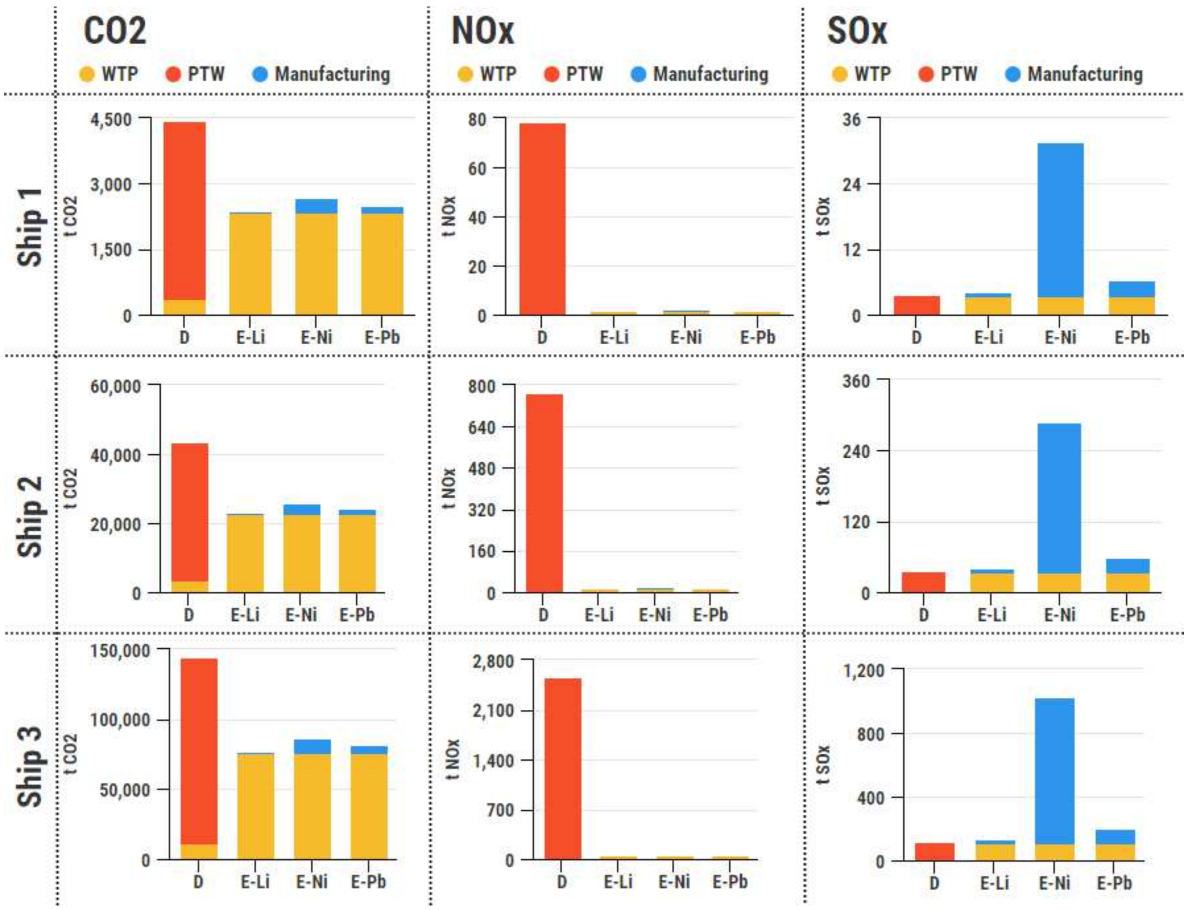


Fig. 5. LCA comparison of existing and alternative all-electric power systems with different batteries

The comparative LCCA of the considered power system on the three different ships is performed and the results are presented in Fig. 6.

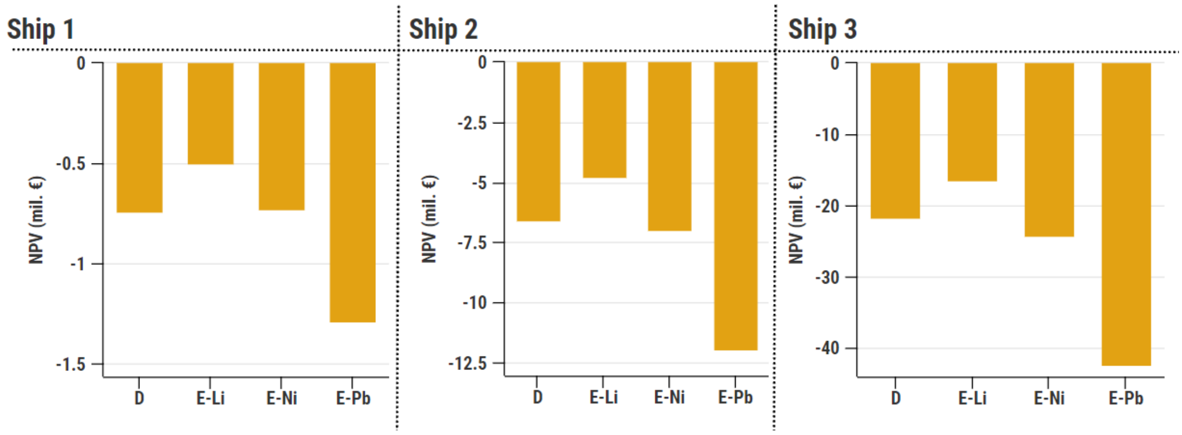


Fig. 6. The LCCA comparison of existing and alternative all-electric power systems with different batteries

The LCA results in Fig. 5 indicate that the most environmentally friendly option to replace the diesel-powered ship is electrification with a Li-ion battery. This option resulted in about 46% lower $CO_2$ emissions, around 98% lower $NO_X$ emissions, and around 13% higher $SO_X$ emissions. Their major contributor is the WTP phase, i.e. the electricity production. The used European electricity mix, Fig. 4, constitutes of 42.1% of fossil fuels, 26.6% of nuclear fuel and 31.3% of RESs. The higher share of RESs in the electricity mix would result in lower emissions. The Li-ion battery represents the most ecological solution among other batteries mainly due to longer lifetime of the battery and higher energy density, resulting in a lower weight of the battery and consequently lower manufacturing emissions. The performed analysis also indicated that the process of manufacturing the Ni-MH battery results with the highest emissions among other considered batteries, especially the $SO_X$ emissions which are for each ship around 89% higher than emissions related to the diesel-powered ship.

The LCCA comparison, Fig. 6, highlighted the electrification with a Li-ion battery as the most cost-effective option for the replacement of the existing power system. The total cost are converted to the *NPV* in order for the life-cycle costs of different power systems could be compared. The ship with a Li-ion battery resulted in lower costs than the diesel-powered ship (Ship 1: 32%; Ship 2: 27%; Ship 3: 24%). These results revealed that electrification with a Li-ion battery is more cost-effective when it is applied on a smaller ship that operates on shorter routes. This is mainly due to the investment costs of the required battery capacity and average power of a ship.

By taking Ship 2 as the test case, the *ROI* is calculated and at the end of a considered lifetime and is equal to 306%, while the discounted payback period accounts for 5 years. The evaluation of the profitability of retrofitting the diesel-powered ship (Ship 2) with a Li-ion battery is calculated by using the IRR function in Microsoft Excel. Since *IRR* depends on different costs, the sensitivity analysis is performed, where the diesel, electricity and battery prices are varied by ± 20%, with an increment of 10%, Fig. 7.

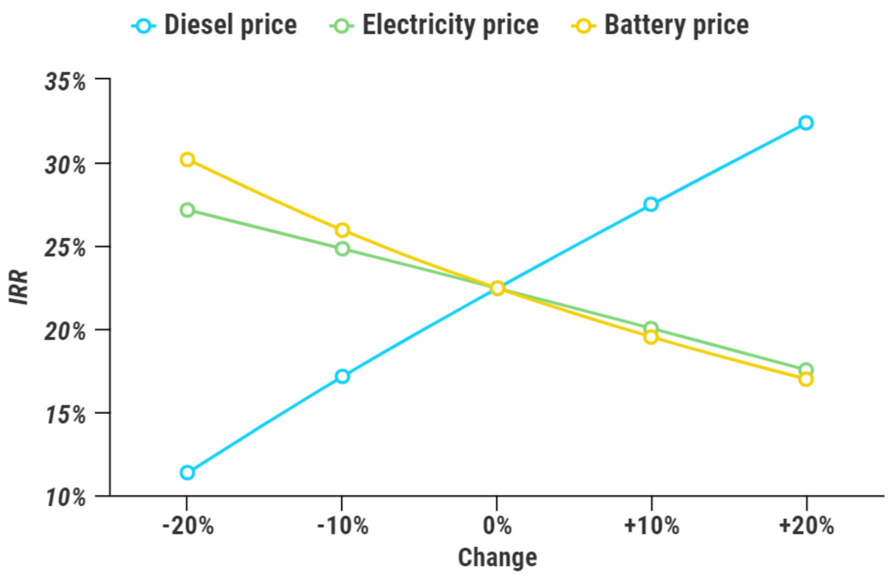

Fig. 7. Effect of individual costs on the *IRR* of the considered system

The *IRR* of the considered system is 22.44%, which indicates that the retrofit of the existing Ship 2 with a Li-on battery is acceptable as the *IRR* is higher than the default discount rate of 5%. By increasing the price of diesel, the *IRR* is increasing, while by decreasing the price of a battery, which is possible with further development of battery technology, the *IRR* is also increasing.

The nexus between performed LCA and LCCA is presented in the penalization of the emissions released by the powe system. The emission expense, *EmEx*, expressed in € per ton of released emissions, is obtained from a study by Gonçalves Castro et al [102]. In that study, the $CO_2$ cost is divided into three scenarios (low, moderate and high) in which prices for 1 ton of $CO_2$ increase during the period from 2020 to 2050, while the $NO_X$ and $SO_X$ costs remain the same during the observed period, Fig. 8. The initial $CO_2$ price in 2021 for the different scenarios is modified with the current price of EU carbon permits, i.e. 59 €/ton [103], while the analysis is made for the 20 years of ship lifetime, from 2021 to 2041.

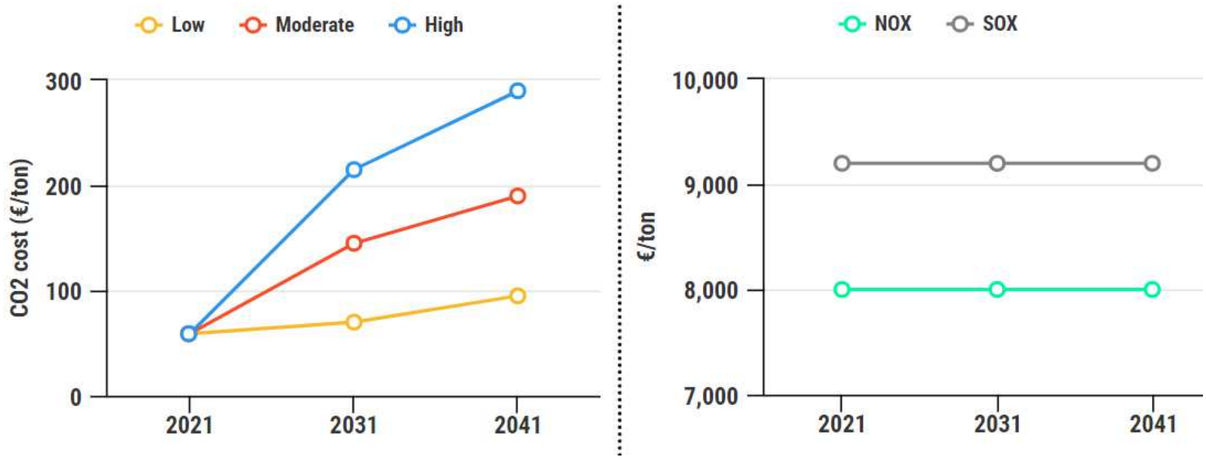


Fig. 8. The costs of $CO_2$, $NO_X$ and $SO_X$ emissions according to [102]

With the implementation of such emission penalization, the total costs of a diesel-powered ship would be significantly higher, such as presented in Fig. 9, where the implementation of *EmEx* is illustrated on diesel-powered Ship 2, based on different scenarios, i.e. low (D-L), moderate (D-M) and high (D-H) emission prices scenarios.

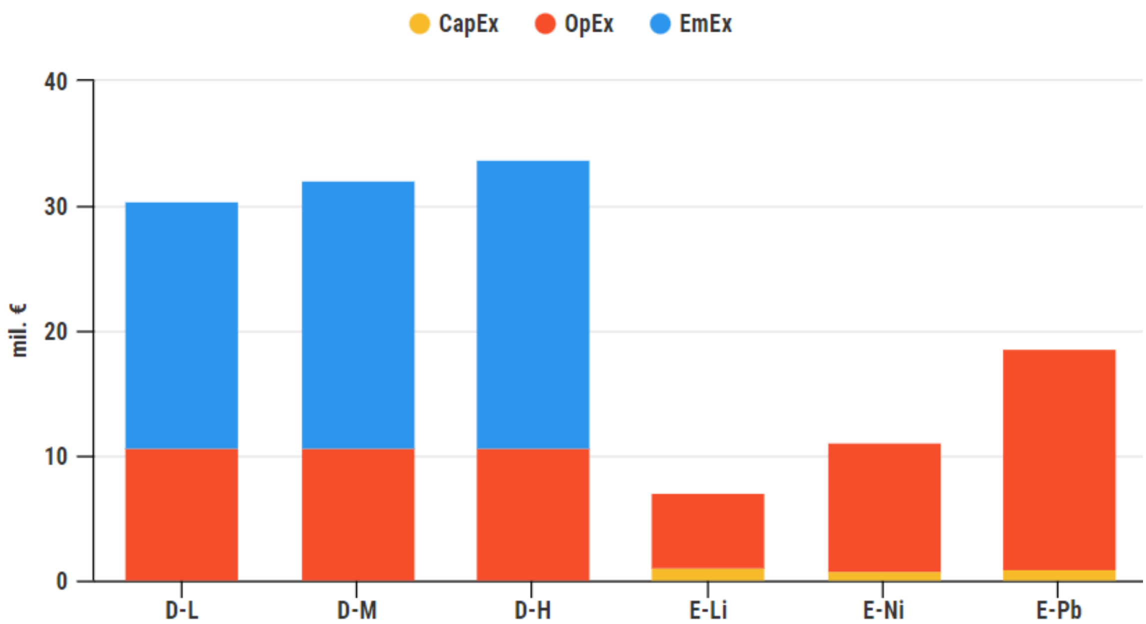


Fig. 9. Comparison of LCCA results of different power systems with respect to *EmEx* scenarios implementation

Inclusion of emissions costs in the shipping sector would represent a great incentive toward electrification of ships since even by the implementation of the D-L scenario, the diesel-powered ship resulted in higher total costs for 84%.

The environmental and economic analysis revealed that the electrification of a ship with a Li-ion battery is the best solution for the decarbonization of the Croatian coastal shipping sector. However, some weaknesses and limitations of the performed analyses are identified. The main limitation is that the system boundary is fixed on the ship power system and not on the entire ship. Nonetheless, this approach provides a comparison of the environmental impact and costs, which is substantial enough for the identification of the best option for a particular ship. Also, the diesel distribution process and crude oil transportation to the refinery is considered in a simplified way, but that has no major impact on the results. Another weakness is the calculation of battery characteristics, where the energy density and the lifetime of the considered batteries are assumed to be equal to the upper limits of a particular range. The potential increase in fuel prices and battery costs in the future is not considered, and the cost assessments are following the business-as-usual scenario.

Furthermore, the investigation was focused only on the commercially available batteries which parameters are included in the GREET 2020 database. The recycling process of the batteries is not included in the analyses, but it can be incorporated in the model, where the emissions related to certain batteries will be higher. For example, the Pb-acid battery is a highly recyclable battery, unlike the Li-ion batteries which recycling process is rather difficult since it is made of many compounds.

## 5. Conclusion

The consumption of fossil fuel and its impact on the environment are gradually shifting the shipping industry towards the implementation of decarbonization measures defined in strategies and regulations. One of the measures that represent a viable option for future shipping, resulting in reduced fuel consumption and shipping emissions, is the replacement of conventional mechanical propulsion with electric propulsion. Moreover, the full electrification of ships with only a battery as a power source is one of the alternatives towards achieving zero-emission shipping.

In this paper, the review of battery technologies for shipping purposes is presented. Among different battery technologies (Li-ion, Ni-MH, Pb-acid), the Li-ion battery is highlighted as the most prominent for ship electrification. In order to satisfy the high requirements of batteries in ships, significant research effort is devoted to improving existing battery systems using advanced techniques and processes of emerging energy technologies. Development of the state-of-the-art rechargeable battery technologies requires a precise match between the particular subsector requirements of maritime transport and the electrochemical indicators of the energy storage process. Further investigation of considered batteries was performed from the environmental and economical points of view. The LCA and LCCA were performed to highlight the most environmentally friendly and the most cost-effective battery implemented on a ship. The three ships engaged in the Croatian short-sea shipping sector are taken as a case study. The main findings of the performed assessments can be summarized as follows:

- The LCA indicated that a ship's electrification with a Li-ion battery represents the most environmentally friendly option with the $CO_2$ reduction of 46% and $NO_X$ reduction of 98%, compared to the diesel power system. However, the increase of $SO_X$ emissions for around 13% is noticed in comparison to the existing power system. The LCA also indicated that the Ni-MH battery's manufacturing process releases a large amount of $SO_X$ emissions and that the electrification of a ship with Ni-MH battery results in 89% higher $SO_X$ emissions than a diesel-powered ship.
- The LCCA highlighted electrification with a Li-ion battery as the most cost-effective alternative for replacing diesel power systems. It is noticed that the cost reduction for Ship 1 (32%) is higher than is the case for Ship 3 (24%). This is mainly due to the investment costs of the required battery capacity and average power of a ship.
- The sensitivity analysis indicated that the cost-effectiveness of the electrification of Ship 2 with a Li-ion battery is viable. Moreover, by increasing the cost of diesel fuel, which is probable in the near future, the cost-effectiveness is higher.
- The inclusion of costs for $CO_2$, $NO_X$ and $SO_X$ emissions would represent a great incentive toward the ship electrification since these costs depend on the amount of emissions caused by fuel combustion. Even with the a low emission cost scenario, the analysis indicated that the total costs of the diesel-powered ship increased for around 84%.

The full electrification with currently available battery technology is feasible for the ships that operate within the short-sea shipping sector, such as presented in the case study. However, the further development of storage technology would open the pathway for full electrification of ships that operate on longer routes.

**Acknowledgement**

This research was supported by the Croatian Science Foundation under the project Green Modular Passenger Vessel for Mediterranean (GRiMM), (Project No. UIP-2017-05-1253) conducted by the University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture (Croatia) as well as the project Strengthening Transnational Co-operation, Knowledge and Technology Transfer in Development of Electric Vessels and Fostering Innovations in SME's (ZEVinnovation), (Project Index No. 2018-1-1185) funded by Iceland, Liechtenstein and Norway through the EEA and Norway Grants Fund for Regional Cooperation and conducted by the Center of Technology Transfer LLC (Croatia). Maja Perčić, a Ph.D. Student, is supported through the "Young researchers' career development project – training of doctoral students" of the Croatian Science Foundation, funded by the European Union from the European Social Fund.

The LCA analysis in this study was performed using GREET 2020 software produced by UChicago Argonne, LLC under Contract No. DE-AC02-06CH11357 with the Department of Energy.

## REFERENCES


[1] Gu Y, Wallace SW, Wang X. Can an Emission Trading Scheme really reduce CO2 emissions in the short term? Evidence from a maritime fleet composition and deployment model. Transp Res Part D Transp Environ, 2019;74:318–38.

[2] Lu Y, Shao M, Zheng C, Ji H, Gao X, Wang Q. Air pollutant emissions from fossil fuel consumption in China: Current status and future predictions. Atmos Environ, 2020;231:117536.

[3] Monteiro A, Russo M, Gama C, Borrego C. How important are maritime emissions for the air quality: At European and national scale. Environmental Pollution, 2018;242:565–75.

[4] Bataille C, Åhman M, Neuhoff K, Nilsson LJ, Fischedick M, Lechtenböhmer S, Solano-Rodriquez B, Denis-Ryan A, Steiber S, Waisman H, Sartor O, Rahbar S. A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. Journal of Cleaner Production 2018;187:960–73.

[5] International Maritime Organization (IMO). Reduction of GHG emissions from ships. Fourth IMO GHG Study 2020 - Final report, https://safety4sea.com/wp-content/uploads/2020/08/MEPC-75-7-15-Fourth-IMO-GHG-Study-2020-Final-report-Secretariat.pdf; 2020 [accessed 10 November 2020].

[6] ben Brahim T, Wiese F, Münster M. Pathways to climate-neutral shipping: A Danish case study. Energy, 2019;188:116009.

[7] Chen L, Yip TL, Mou J. Provision of Emission Control Area and the impact on shipping route choice and ship emissions. Transp Res Part D Transp Environ, 2018;58:280–91.

[8] Sui C, de Vos P, Stapersma D, Visser K, Ding Y. Fuel consumption and emissions of ocean-going cargo ship with hybrid propulsion and different fuels over voyage. J Mar Sci Eng, 2020;8.

[9] Bouman EA, Lindstad E, Rialland AI, Strømman AH. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review. Transportation Research Part D Transport Environment, 2017;52:408–21.

[10] Bach H, Bergek A, Bjørgum Ø, Hansen T, Kenzhegaliyeva A, Steen M. Implementing maritime battery-electric and hydrogen solutions: A technological innovation systems analysis. Transp Res Part D Transp Environ, 2020;87:102492.

[11] Zahedi B, Norum LE, Ludvigsen KB. Optimized efficiency of all-electric ships by dc hybrid power systems. Journal of Power Sources, 2014;255:341–54.

[12] Wu P, Partridge J, Bucknall R. Cost-effective reinforcement learning energy management for plug-in hybrid fuel cell and battery ships. Applied Energy, 2020;275:115258.

[13] Nuchturee C, Li T, Xia H. Energy efficiency of integrated electric propulsion for ships – A review. Renew Sustain Energy Rev, 2020;134:110145.

[14] Sterling PlanB Energy Solutions. Electrification of ships, https://spbes.com/; 2021 [accessed 13 January 2021].

[15] Dedes EK, Hudson DA, Turnock SR. Assessing the potential of hybrid energy technology to reduce exhaust emissions from global shipping. Energy Policy, 2012;40:204–18.

[16] Jianyun Z, Li C, Lijuan X, Bin W. Bi-objective optimal design of plug-in hybrid electric propulsion system for ships. Energy, 2019;177:247–61.

[17] Gagatsi E, Estrup T, Halatsis A. Exploring the Potentials of Electrical Waterborne Transport in Europe: The E-ferry Concept. Transportation Resesearch Procedia, 2016;14:1571–80.

[18] Geertsma RD, Negenborn RR, Visser K, Hopman JJ. Design and control of hybrid power and propulsion systems for smart ships: A review of developments. Applied Energy, 2017;194:30–54.

[19] Jafarzadeh S, Schjølberg I. Operational profiles of ships in Norwegian waters: An activity-based approach to assess the benefits of hybrid and electric propulsion. Transportation Research Part D: Transport and Environment, 2018;65:500–23.

[20] Ritari A, Huotari J, Halme J, Tammi K. Hybrid electric topology for short sea ships with high auxiliary power availability requirement. Energy, 2020;190:116359.

[21] Lindstad HE, Eskeland GS, Rialland A. Batteries in offshore support vessels – Pollution, climate impact and economics. Transporation Research Part D: Transport and Environment, 2017;50:409–17.

[22] Balsamo F, Capasso C, Lauria D, Veneri O. Optimal design and energy management of hybrid storage systems for marine propulsion applications. Applied Energy, 2020;278:115629.

[23] Ampere Electric-Powered Ferry - Ship Technology. https://www.ship-technology.com/projects/norled-zerocat-electric-powered-ferry/;2020 [accessed January 21, 2021].

[24] Nitta N, Wu F, Lee JT, Yushin G. Li-ion battery materials: Present and future. Materials Today, 2015;18:252–64.

[25] Marques P, Garcia R, Kulay L, Freire F. Comparative life cycle assessment of lithium-ion batteries for electric vehicles addressing capacity fade. Journal of Cleaner Production, 2019;229:787–94.

[26] Qadrdan M, Jenkins N, Wu J. Smart grid and energy storage. McEvoy's Handb. Photovoltaics Fundam. Appl. Third Edit, Elsevier Ltd; 2018, p. 915–28.

[27] Chen H, Cong TN, Yang W, Tan C, Li Y, Ding Y. Progress in electrical energy storage system: A critical review. Progress in Natural Science, 2009;19:291–312.

[28] Liang Y, Zhao C, Yuan H, Chen Y, Zhang W, Huang J, et al. A review of rechargeable batteries for portable electronic devices. InfoMat, 2019;1:6–32.

[29] Fetcenko MA, Ovshinsky SR, Reichman B, Young K, Fierro C, Koch J, et al. Recent advances in NiMH battery technology. Journal of Power Sources, 2007;165:544–51.

[30] Wu P, Bucknall R. Marine propulsion using battery power. Shipping in Changing Climates Conference, 2016:1–10.

[31] Kurzweil P, Garche J. Overview of batteries for future automobiles. Lead-Acid Batter. Future Automobiles, Elsevier B.V.; 2017, p. 27–96.

[32] Iclodean C, Varga B, Burnete N, Cimerdean D, Jurchiş B. Comparison of Different Battery Types for Electric Vehicles. IOP Conference Series: Materials Science and Engineering, 2017;252.

[33] Ding YL, Cano ZP, Yu A, Lu J, Chen Z. Automotive Li-Ion Batteries: Current Status and Future Perspectives. Journal of Chemical Information and Modeling, 2013;53:1689–99.

[34] Axsen J, Burke AF, Kurani KS. Batteries for PHEVs: Comparing Goals and the State of Technology. Electric and Hybrid Vehicles, Elsevier B.V; 2010, p. 405–27.

[35] Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied Energy, 2015;137:511–36.

[36] European Automobile Manufacturers Association. A review of battery technologies for automotive applications, https://www.acea.be/uploads/publications/Rev_of_Battery_technology_-_full_report.pdf; 2015 [accessed 02 January 2021].

[37] Zhu WH, Zhu Y, Davis Z, Tatarchuk BJ. Energy efficiency and capacity retention of Ni-MH batteries for storage applications. Applied Energy, 2013;106:307–13.

[38] Zubi G, Dufo-López R, Carvalho M, Pasaoglu G. The lithium-ion battery: State of the art and future perspectives. Renewable and Sustainable Energy Reviews 2018;89:292–308.

[39] MAN Energy Solutions. Technical papers, Batteries on board ocean-going vessels, https://www.man-es.com/docs/default-source/marine/tools/batteries-on-board-ocean-going-vessels.pdf?sfvrsn=deaa76b8_14; 2019 [accessed 13 December 2020].

[40] Yu Y, Mao J, Chen X. Comparative analysis of internal and external characteristics of lead-acid battery and lithium-ion battery systems based on composite flow analysis. Science of The Total Environment, 2020;746:140763.

[41] Rand DAJ, Moseley PT. Secondary Batteries - Lead- Acid Systems | Overview. Encyclopedia of Electrochemical Power Sources, 2009:550–75.

[42] Hariprakash B, Shukla A, Venugoplan S. Secondary Batteries – nickel systems | Nickel–Metal Hydride: Overview. Encyclopedia of Electrochemical Power Sources, 2009, p. 494–501.

[43] Sundén B. Applications of batteries. Hydrogen, Batteries and Fuel Cells, 2019, p. 111–22.

[44] EMSA European Maritime Safety Agency. Electrical Energy Storage for Ships, http://www.emsa.europa.eu/publications/corporate-publications/download/6186/3895/23.html; 2020 [accessed November 3, 2020].

[45] Armand M, Axmann P, Bresser D, Copley M, Edström K, Ekberg C, et al. Lithium-ion batteries – Current state of the art and anticipated developments. Journal of Power Sources, 2020;479.

[46] Liu W, Liu H, Liu W, Cui Z. Life cycle assessment of power batteries used in electric bicycles in China. Renewable and Sustainable Energy Reviews, 2020;139:110596.

[47] Ayers W, Bay E. Comparative Payback of Lithium-Ion Batteries for Pacific NW Ferries 2016:1–7.

[48] Chen Y, Song S, Zhang X, Liu Y. The challenges, solutions and development of high energy Ni-rich NCM/NCA LiB cathode materials. Journal of Physics: Conference Series, 2019;1347.

[49] Degiuli N, Ćatipović I, Martić I, Werner A, Čorić V. Increase of ship fuel consumption due to the added resistance in waves. Journal of Sustainable Development of Energy Water and Environment Systems, 2017;5:1–14.

[50] Gourley SWD, Or T, Chen Z. Breaking Free from Cobalt Reliance in Lithium-Ion Batteries. IScience, 2020;23:101505.

[51] Chombo PV, Laoonual Y. A review of safety strategies of a Li-ion battery. Journal of Power Sources, 2020;478:228649.

[52] Xiong R, Sun W, Yu Q, Sun F. Research progress, challenges and prospects of fault diagnosis on battery system of electric vehicles. Applied Energy, 2020;279:115855.

[53] Niu X, Garg A, Goyal A, Simeone A, Bao N, Zhang J, et al. A coupled electrochemical-mechanical performance evaluation for safety design of lithium-ion batteries in electric vehicles: An integrated cell and system level approach. Journal of Cleaner Production, 2019;222:633–45.

[54] Ren D, Feng X, Liu L, Hsu H, Lu L, Wang L, et al. Investigating the relationship between internal short circuit and thermal runaway of lithium-ion batteries under thermal abuse condition. Energy Storage Materials, 2020;34.

[55] Auger DJ, Groff MF, Mohan G, Longo S, Assadian F. Impact of battery ageing on an electric vehicle powertrain optimisation. Journal of Sustainable Development of Energy Water and Environment Systems, 2014;2:350–61.

[56] Beltran H, Ayuso P, Pérez E. Lifetime Expectancy of Li-Ion Batteries used for Residential Solar Storage. Energies 2020;13.

[57] Perčić M, Ančić I, Vladimir N. Life-cycle cost assessments of different power system configurations to reduce the carbon footprint in the Croatian short-sea shipping sector. Renewable and Sustainable Energy Reviews, 2020;131:110028.

[58] International Organization for Standardization (ISO). ISO 14040, https://www.iso.org/standard/37456.html; 2006 [accessed 12 December 2020].

[59] Blanco-Davis E, Zhou P. LCA as a tool to aid in the selection of retrofitting alternatives. Ocean Engineering 2014;77:33–41.

[60] DNV. Achieving the IMO decarbonization goals, https://www.dnv.com/expert-story/maritime-impact/How-newbuilds-can-comply-with-IMOs-2030-CO2-reduction-targets.html; 2021 [accessed 20 October 2021].

[61] Sharafian A, Blomerus P, Mérida W. Natural gas as a ship fuel: Assessment of greenhouse gas and air pollutant reduction potential. Energy Policy, 2019;131:332–46.

[62] Manouchehrinia B, Dong Z, Gulliver TA. Well-to-Propeller environmental assessment of natural gas as a marine transportation fuel in British Columbia, Canada. Energy Reports, 2020;6:802–12.

[63] Cucinotta F, Raffaele M, Salmeri F, Sfravara F. A comparative Life Cycle Assessment of two sister cruise ferries with Diesel and Liquefied Natural Gas machinery systems. Applied Ocean Research, 2021;112:102705.

[64] Ling-Chin J, Heidrich O, Roskilly AP. Life cycle assessment (LCA) – from analysing methodology development to introducing an LCA framework for marine photovoltaic (PV) systems. Renewable and Sustainable Energy Reviews, 2016;59:352–78.

[65] Park T, So S, Jeong B, Zhou P, Lee J ung. Life cycle assessment for enhanced Re-liquefaction systems applied to LNG carriers; effectiveness of partial Re-liquefaction system. Journal of Cleaner Production, 2021;285:124832.

[66] Jang H, Jeong B, Zhou P, Ha S, Nam D, Kim J, et al. Development of Parametric Trend Life Cycle Assessment for marine SOx reduction scrubber systems. Journal of Cleaner Production, 2020;272:122821.

[67] Strazza C, Del Borghi A, Costamagna P, Traverso A, Santin M. Comparative LCA of methanol-fuelled SOFCs as auxiliary power systems on-board ships. Applied Energy, 2010;87:1670–8.

[68] Jeong B, Jeon H, Kim S, Kim J, and Zhou P. Evaluation of the lifecycle environmental benefits of full battery powered ships: Comparative analysis of marine diesel and electricity. *J. Mar. Sci. Eng.*, 2020; 8(8):580.

[69] Sandnes Galaaen J. Comparative Life Cycle Assessment of a Diesel Electric and a Battery Electric Ferry [master's thesis]. Norweigan University of Science and Technology. Department of Marine Technology, 2020, Available:

https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2491124/15570_FULLTEXT.pdf?sequence=1&isAllowed=y [accessed : 6 March 2022].

[70] Kjær LL, Pagoropoulos A, Hauschild M, Birkved M, Schmidt JH, McAloone TC. From LCC to LCA Using a Hybrid Input Output Model – A Maritime Case Study. Procedia CIRP, 2015;29:474–9.

[71] Wang C, Ju Y, Fu Y. Comparative life cycle cost analysis of low pressure fuel gas supply systems for LNG fueled ships. Energy, 2021;218:119541.

[72] Jovanović I, Vladimir N, Perčić M, and Koričan M. The feasibility of autonomous low-emission ro-ro passenger shipping in the Adriatic Sea. Ocean Eng., 2022; 247:110712.

[73] Korberg A. D., Brynolf S., Grahn M., and Skov I. R. Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. *Renew. Sustain. Energy Rev.*, 2021; 142:110861.

[74] Wang H, Oguz E, Jeong B, Zhou P. Life cycle cost and environmental impact analysis of ship hull maintenance strategies for a short route hybrid ferry. Ocean Engineering, 2018;161:20–8.

[75] Jeong B, Wang H, Oguz E, Zhou P. An effective framework for life cycle and cost assessment for marine vessels aiming to select optimal propulsion systems. Journal of Cleaner Production, 2018;187:111–30.

[76] Wang H, Boulougouris E, Theotokatos G, Zhou P, Priftis A, Shi G. Life cycle analysis and cost assessment of a battery powered ferry. *Ocean Eng.*, 2021; 241:110029.

[77] Wang H, Oguz E, Jeong B, Zhou P. Life cycle and economic assessment of a solar panel array applied to a short route ferry. J. Clean. Prod., 2019; 219:471–484.

[78] Perčić M, Ančić I, and Vladimir N. Life-cycle cost assessments of different power system configurations to reduce the carbon footprint in the Croatian short-sea shipping sector. *Renew. Sustain. Energy Rev.*, 2020; 131:110028.

[79] Perčić M, Vladimir N, Fan A. Life-cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short-sea shipping: A case study of Croatia. Applied Energy, 2020;279.

[80] Fan A, Wang J, He Y, Perčić M, Vladimir N, Yang L. Decarbonising inland ship power system: Alternative solution and assessment method. Energy, 2021;226.

[81] V. Goel and S. Wadelius. Evaluation of transition towards zero emission commuter ferries. Comparative Analysis of Fuel-based and Battery-based Marine Propulsion System from financial and environmental perspectives [Degree project in naval architecture]. KTH Royal Institute of Technology. Engineering sciences. 2021, Available: **https://www.diva-portal.org/smash/get/diva2:1599580/FULLTEXT01.pdf** [accessed: 5 March 2022].

[82] Perčić M, Vladimir N, Fan A. Techno-economic assessment of alternative marine fuels for inland shipping in Croatia. Renewable and Sustainable Energy Reviews 2021;148:111363.

[83] Xing H, Spence S, Chen H. A comprehensive review on countermeasures for CO2 emissions from ships. Renewable and Sustainable Energy Reviews 2020;134:110222.

[84] Chen K, Kim S, Je M, Choi H, Shi Z, Vladimir N, et al. Ultrasonic Plasma Engineering Toward Facile Synthesis of Single-Atom M-N4/N-Doped Carbon (M = Fe, Co) as Superior Oxygen Electrocatalyst in Rechargeable Zinc–Air Batteries. Nano-Micro Lett, 2021;13.

[85] Saboori H, Jadid S. Optimal scheduling of mobile utility-scale battery energy storage systems in electric power distribution networks. Journal of Energy Storage 2020;31:101615.

[86] Zhou Z, Benbouzid M, Frédéric Charpentier J, Scuiller F, Tang T. A review of energy storage technologies for marine current energy systems. Renewable and Sustainable Energy Reviews 2013;18:390–400.

[87] Duffner F, Mauler L, Wentker M, Leker J, Winter M. Large-scale automotive battery cell manufacturing: Analyzing strategic and operational effects on manufacturing costs. International Journal of Production Economics 2021;232:107982.

[88] International Organization for Standardization (ISO). ISO 14044, https://www.iso.org/standard/38498.html; 2006 [accessed 12 December 2020].

[89] Torbianelli VA. When the road controls the sea: a case study of Ro-Ro transport in the Mediterranean. Maritime Policy & Management, 2000;27:375–89.

[90] Ančić I, Perčić M, Vladimir N. Alternative power options to reduce carbon footprint of ro-ro passenger fleet: A case study of Croatia. Journal of Cleaner Production 2020;271.

[91] United Nations. Review of Maritime Transport: Structure, ownership and registration of the world fleet, https://unctad.org/system/files/official-document/rmt2017ch2_en.pdf 2018 [accessed 20 October 2021].

[92] Jadrolinija. Croatian ferries, https://www.jadrolinija.hr/o-nama/brodovi/trajekti/trajekti-lokalnih-linija; 2020 [accessed 10 December 2020].

[93] Croatian Register of Shipping. Web report of a ship, http://report.crs.hr/hrbwebreports/Default.aspx; 2020 [accessed December 10, 2020].

[94] Jadrolinija. Ferry lines schedule, https://www.jadrolinija.hr/red-plovidbe/lokalne-linije-2020-; 2020 [accessed December 10, 2020].

[95] INA. Motor fuels, https://www.ina.hr/en/home/customers/products-and-services/motor-fuels/; 2020 [accessed 12 December 2020].

[96] International Maritime Organization (IMO). Third IMO Greenhouse Gas Study 2014, https://www.imo.org/en/OurWork/Environment/Pages/Greenhouse-Gas-Studies-2014.aspx; 2014 [accessed 08 December 2020].

[97] Ančić I, Vladimir N, Cho DS. Determining environmental pollution from ships using Index of Energy Efficiency and Environmental Eligibility (I4E). Marine Policy 2018;95:1–7.

[98] Pelletier S, Jabali O, Laporte G, Veneroni M. Battery degradation and behaviour for electric vehicles: Review and numerical analyses of several models. Transportation Research Part B: Methodological 2017;103:158–87.

[99] Iannaccone T, Landucci G, Tugnoli A, Salzano E, Cozzani V. Sustainability of cruise ship fuel systems: Comparison among LNG and diesel technologies. Journal of Cleaner Production, 2020;260:121069.

[100] European Commmission. Energy prices and costs in Europe, https://ec.europa.eu/energy/sites/ener/files/documents/annex_3_-_country_sheets_-part_4_of_4_post_isc-v2.pdf; 2018 [accessed April 25, 2020].

[101] Christos B. Techno - economical feasibility study on the retrofit of double - ended Ro / Pax ferries into battery - powered ones Techno - economical feasibility study on the retrofit of double - ended Ro / Pax ferries into battery - powered ones. 2017.

[102] Gonçalves Castro M, Mestemaker B, Van Den Heuvel H. Towards zero emission work vessels: the case of a dredging vessel. Proceding of 2nd International Conference On Modelling and Optimisation of Ship Energy Systems, Glasgow, Scotland, United Kingdom: 2019.

[103] EU Carbon Permits (2021 Data). https://tradingeconomics.com/commodity/carbon; [accessed November 10, 2021].