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Article

Environmental and Economic Assessment of Batteries for Marine Applications: Case Study of All-Electric Fishing Vessels

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Abstract: The increasing global warming problem has pushed the community to implement emission reduction measures in almost every segment of human life. Since the major source of anthropogenic Greenhouse Gases (GHGs) is fossil fuel combustion, in the shipping sector, these measures are oriented toward a reduction in tailpipe emissions, where the replacement of traditional internal combustion marine engines with zero-carbon technologies offers the ultimate emission reduction results. According to the International Maritime Organization (IMO) GHG strategy, vessels involved in international shipping must achieve a minimum 50% reduction in their GHG emissions by 2050. However, this requirement does not extend to fishing vessels, which are significant consumers of fossil fuels. This paper deals with the full electrification of two types of fishing vessels (purse seiners and trawlers), wherein different Lithium-ion Batteries (LiBs) are considered. To investigate their environmental footprint and profitability, Life-Cycle Assessments (LCAs) and Life-Cycle Cost Assessments (LCCAs) are performed. The comparison of all-electric fishing vessels with existing diesel-powered ships highlighted the Lithium Iron Phosphate (LFP) battery as the most suitable alternative powering option regarding environmental and economic criteria.

Keywords: fishing sector; decarbonization; all-electric ship; battery; LCA; LCCA

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1. Introduction

1.1. Research Background

Ships are mainly powered by Heavy Fuel Oil (HFO) or Marine Diesel Oil (MDO), whose combustion in the ship engine results in a great amount of harmful emissions, such as nitrogen oxide (NO_X), sulfur oxide (SO_X), and particulate matter (PM), but also Greenhouse Gases (GHGs), due to the high carbon content [1]. Increased shipping emissions forced the International Maritime Organization (IMO) to set a strategy for their reduction. The focus of that strategy is on GHGs, which refer to the emissions of carbon dioxide (CO_2) as the main GHGs, but also methane (CH_4), and nitrous oxide (N_2O), whose rising concentration in the atmosphere causes global warming [2]. According to the IMO GHG strategy, each ship engaged in international shipping needs to reduce its annual GHG emissions by at least 50% by 2050 compared to the 2008 level [3]. The strategy outlines decarbonization measures delineated across three distinct timelines: short-term (2018–2023), mid-term (2023–2030), and long-term (2030 onwards). The short-term measures relate to efforts commencing to curtail shipping emissions, encompassing national plans, enhanced Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan (SEEMP) and speed reduction [4]. One of the mid-term measures is the implementation of a new ship energy efficiency regulative for existing ships, i.e., Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII), which became effective on 1 January 2023 [5]. The long-term measure of IMO's GHG strategy and the game-changer for the decarbonization of the shipping sector is the replacement of conventional fuels with alternatives with an emphasis on zero-carbon fuels like hydrogen, ammonia and electricity, resulting in no tailpipe emissions. Among zero-carbon powering options, electrification represents the most familiar and commercially available technology that is already applied in the shipping sector [6,7].

1.2. Electrification of Ships

Electric propulsion is widely investigated for short-sea vessels [8], tugboats [9], fishing vessels [10], cruise ships [11], icebreakers, naval ships and cable layers [12]. Nuchturee et al. [13] investigated integrated electric propulsion and concluded that battery technology is the dominant storage technology for the electrification of ships due to its reliability, higher energy density and lower costs compared to supercapacitors and flywheels. Three types of electrified ships use batteries, i.e., hybrid ships, plug-in hybrid ships and all-electric ships [14]. Plug-in hybrid and hybrid ships combine a diesel engine with a battery, while an all-electric ship represents a ship that operates solely on a battery. The latter electrification option eliminates tailpipe emissions released during the ship's operation and reduces vibrations and noise that affect marine life [15]. One of the limitations of sole battery use for ship power needs is the distance the ship is operating on, i.e., the range of a trip, which is dependent on the energy density of a battery. Due to limited space to store enough batteries to power the ship on a long-haul trip, full electrification is usually limited to the ships that operate near the coast. Another limitation is the high investment cost, which depends on battery size and the market, i.e., current battery price [16,17].

Since all-electric ships provide zero-emission shipping, and electricity production contributes to its environmental footprint depending on its electricity mix, it is necessary to perform a Life-Cycle Assessment (LCA), which refers to the evaluation of the emissions related to the entire life-cycle of a product. Also, the profitability of alternative power systems plays a significant role in their implementation by shipowners and ship operators. Such an economic analysis is often performed throughout the entire lifetime of a ship with a Life-Cycle Cost Assessment (LCCA). The combination of LCA and LCCA is used to thoroughly investigate the implementation of alternative powering on board a particular ship [18].

Perčić et al. [18] analyzed the electrification of a ferry. Firstly, the ship was powered only by a battery, while in the second case, the ship was powered by a combination of a battery and a PV system. According to the LCA and LCCA results, the all-electric ship is the most environmentally friendly and cost-efficient powering option among those considered. Wang et al. [19] also investigated the full electrification of a ferry, where LCA and LCCA showed that an all-electric ferry results in 30% lower GHGs and 15% lower costs compared to a conventional power system (diesel engine). The analysis of different alternative fuels on board ferries was conducted by Perčić et al. [20], showing that an all-electric ship represents the most environmentally friendly and cost-efficient alternative option, particularly compared to the existing diesel power system. Similar research was conducted for inland ships (tanker, small passenger ship and dredger). LCA results showed that an all-electric ship represents the alternative with the lowest CO_2 emissions for each type of vessel, but it is the economical option only for a small passenger ship due to the high-power needs of a tanker and dredger [21].

Multiple battery types are available on the market. Nevertheless, Lithium-ion Batteries (LiBs) stand out as the predominant technology owing to their high energy density, extended lifespan, and minimal environmental impact [22]. Compared to Nickel-Metal Hydride (Ni-MH) and Lead-acid (Pb-acid) batteries, LiB represents the most environmentally friendly and cost-effective alternative options [23]. The chemical composition of each battery technology determines the characteristics of a battery. LiB's chemistries are Lithium Titanium Oxide (LTO), Lithium Iron Phosphate (LFP), Lithium Cobalt Oxide (LCO), Lithium Manganese Oxide (LMO), Lithium Nickel Manganese Cobalt oxide (NMC), and Lithium Nickel Cobalt Aluminum Oxide (NCA) [24]. Their characteristics and applications are presented in Table 1.

Table 1. LiB technologies and their characteristics [25].

LiB Chemistry	Energy Density	Lifetime	Safety	Application
LTO	low	long	high	• electric powertrains • solar-powered streetlight
LFP	moderate	long	high	• portable and stationary devices that need high endurance
LCO	high	moderate	low	• cellphone • laptop • camera
LMO	moderate	short	moderate	• power tools • medical devices • electric powertrains
NMC	high	long	moderate	• e-bike • medical devices • electric vehicles
NCA	high	moderate	low	• medical devices • industrial and electric powertrain

The LCO battery is the most used type of LiB. This battery type has high energy density but is highly thermal unstable, which could lead to the anode overheating. Moreover, the electrolyte is highly flammable, making the battery a fire hazard. LFP offers good performance with low resistance. It is tolerant to full charge conditions, it has a long lifetime, moderate energy density, and better thermal stability than LCO, and it is often used to replace Pb-acid batteries. NMC batteries combine LCO and LMO, which results in high energy density (still lower than LCO), good thermal stability, low internal resistance and the lowest self-heating rate. It represents a great candidate for electric vehicles. There are different cathode material combinations, e.g., NMC111 refers to one-third of nickel, one-third of manganese and one-third of cobalt. Other variations are NMC532, NMC622 and NMC811. Another candidate for an electric vehicle powertrain is an NCA battery, characterized by high energy density and moderate lifetime. The main drawbacks of its use are its high cost and poor safety. LTO represents an anode material, while the cathode is manganese oxide or NMC. Due to that, the battery offers a long lifetime but low energy density. It is thermally stable and operates better at low temperatures than other LiBs [24,25].

The implementation of a battery on board is mainly investigated for short-sea vessels such as ferries. They represent great candidates for full electrification due to the proximity of the shore and operation on fixed routes [26]. However, to achieve full decarbonization of the shipping sector, i.e., total reduction in GHGs by the end of the century, other vessels that do not go under IMO's regulation need to be retrofitted with alternative power systems, preferably with zero-carbon options such as full electrification.

1.3. Types of Fishing Vessels and Their Operations

Modern fisheries are highly dependent on fossil fuel for ship propulsion, gear operation and other activities on board for fish harvesting [27]. The fuel consumption of fisheries is highly variable, and it depends on the target species, operating conditions, gear, size and structure of a vessel, and fishing methods [28,29]. The fishing methods can be classified as passive (pole and line, longlining, gillnets, pots and traps, and fish aggregating devices), and active (trawling, dredging, purse seining) [30,31].

Trawling can be used in midwater and bottom fishing and it requires a cone-like net with a closed-end that holds the catch. The net is towed by one or two ships, i.e., trawlers, and it is designed to catch specific species that live in the great depths or on the bottom. In bottom trawling, the net often interacts with the seabed, which is the main negative effect of this fishing method [28]. Purse seining is another active fishing method. A purse seiner is a ship that targets dense schools of pelagic fish, and for that, it requires a vertical net (purse seine) with floats on the top line to surround the fish and catch with it. After the schools of fish are spotted, a small boat encircles them with the net, while the bottom of the net is then tightened and enclosed, preventing fish escape. The advantage of purse seining over trawling is that the net has no contact with the seabed [31,32]. Furthermore, during their fishing trip, purse seiners spend around 42% of their time cruising, accounting for 56% of total fuel consumption. Compared to trawlers, who consume most of their fuel (68%) on fishing activities, purse seiners would benefit from energy-saving measures regarding propulsion [30]. Purse seiners can harvest great quantities of fish in a single operation, which is not the case for trawlers. Unlike purse seiners, they catch a wide range of fish, often with a higher market value [30].

The primary environmental concern associated with fishing activities is the substantial consumption of fossil fuels, impacting the environment and human health. It accounts for 1.2% of global fossil fuel consumption, which results in 134 million tons of CO_2 emissions [28,29,33]. To reduce their environmental footprint, different emission reduction measures have been investigated, as well as electrification. Kim et al. [10] investigated battery hybrid systems on board fishing boats in Korea and the results indicated a reduction in CO_2 emissions by 8%. The authors highlighted the importance of the electricity mix used for electricity generation and its contribution to life-cycle emissions. However, to achieve greater emission reduction, the fishing vessel needs to be considered for full electrification. Koričan et al. [34] investigated the integration of all-electric fishing vessels into Isolated Energy Systems (IES). The findings demonstrated that these ships have the potential to mitigate the critical surplus in electricity generation, lower operating costs for IES, and decrease emissions by utilizing the island grid for charging. Furthermore, Koričan et al. [35] conducted an environmental and economic analysis of various alternatives implemented on a trawler. The LCA results revealed that a fully electrified vessel is the most environmentally friendly option, while LCCA showed that other alternatives are more cost effective.

1.4. The Aim of this Paper

Fishing vessels are built in different sizes and are equipped with various gear depending on the target species. Operating on variable, often random routes and frequently changing courses, these vessels experience highly fluctuating power needs. Although fishing vessels are not subject to IMO's GHG strategy, the impact of these ships on the environment cannot be neglected.

This paper aims to analyze the replacement of a diesel engine on board two fishing ships (purse seiner and trawler) with a battery in a lifetime framework. Among the different battery types, the LiB is indicated as the most convenient one. Moreover, LiB has different chemistries, i.e., different materials that constitute the electrodes, which offer different characteristics regarding energy density, lifetime, price, safety, etc. By performing environmental and economic analyses with LCA and LCCA, respectively, the life-cycle emissions (GHGs, NO_X, SO_X and PM) and lifetime costs of different LiBs (LFP, NCA, NMC111, NMC532, NMC622, NMC811) are investigated. The LCA and LCCA comparison indicates the most suitable powering option with respect to environmental and economic criteria. To the authors' best knowledge, there are no publicly available studies into different LiBs for the full electrification of fishing vessels.

2. Methodology

2.1. Ship Particulars

The Croatian fishing fleet includes 7808 vessels, among which 56.4% are smaller than 6 m in length [36]. The fleet represents the 6th fleet in the Mediterranean area based on the total capture production, where around 90% of landing weight and 55% of landing values correspond to a catch from purse seiners [37]. With an average age of over 40 years, some improvements regarding power systems would need to be made to Croatian fishing vessels by retrofitting them with new and clean alternatives. In this paper, the evaluation of the electrification of fishing vessels with different batteries is performed, where the Croatian purse seiner and trawler are taken as test cases. Their main particulars are presented in Table 2.

Table 2. The main particulars for considered purse seiner and trawler [36].

	Purse seiner	Trawler
Ship type		
Length overall, (m)	32.28	22.1
Breadth (m)	7.40	5.65
Draught (m)	2.88	1.99
GT (t)	182	65
Main power, P_{ME} (kW)	480	223
Auxiliary power, P_{AE} (kW)	370	35

There are several differences between Croatian purse seiners and trawlers. Purse seiners are powered by engines with an average power of 150–400 kW, while the trawler's average engine power varies between 150 and 250 kW. Purse seiners are greater in length and GT than trawlers. The average length of a purse seiner is 24 m, while for a trawler, it equals 19 m. The average daily operation of purse seiners includes an operation time of the main engines (t_{ME}) of four hours and of the auxiliary engines (t_{AE}) of 15 h, while for trawlers, both the main and auxiliary engines operate daily for 10 h. Both fishing vessels operate around 200 days a year [38].

The energy needs for purse seiner and trawler are calculated using the same equations. The average power of a fishing vessel, P_{ave} (kW) is calculated with the following equation, obtained from [39]:

$$P_{ave} = P_{ME,ave} + P_{AE,ave}, \tag{1}$$

According to Koričan et al. [38], the average power of the main engine, $P_{ME,ave,PS}$ (kW), and auxiliary engine, $P_{AE,ave,PS}$ (kW), for a purse seiner are calculated as follows [38]:

$$P_{ME,ave,PS} = 0.56 \cdot P_{ME}, \tag{2}$$

$$P_{AE,ave,PS} = 0.388 \cdot P_{ME,ave}, \tag{3}$$

while for a trawler, the average power of the main engine, $P_{ME,ave,T}$ (kW), and auxiliary engines, $P_{AE,ave,T}$ (kW), for a trawler is calculated as follows [38]:

$$P_{ME,ave,PS} = 0.68 \cdot P_{ME}, \tag{4}$$

$$P_{AE,ave,PS} = 0.124 \cdot P_{ME,ave}. \tag{5}$$

The annual energy consumption of a ship, EC_A (kWh), is calculated with the following equation, obtained from [39]:

$$EC_A = P_{ME,ave} \cdot t_{ME,A} + P_{AE,ave} \cdot t_{AE,A}, \tag{6}$$

where $t_{ME,A}$ (h) and $t_{AE,A}$ (h) denote the annual operating time of the main engine and auxiliary engines, which equal 800 h and 3000 h for purse seiners and 2000 for trawlers (both engines).

2.2. Life-Cycle Assessment and Life-Cycle Cost Assessment

LCA is a standardized method for evaluating the environmental impact of a product, process or system by investigating released emissions through their life-cycle [40]. According to ISO guidelines [41], there are four phases within the LCA framework: goal and scope, inventory analysis, impact assessment, and interpretation (Figure 1).

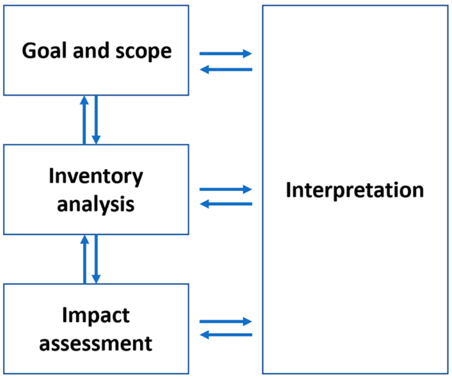

Figure 1. LCA framework.

The initial stage of LCA involves establishing the goal, scope, functional unit, and system boundary and identifying data and impact categories. This paper aims to investigate different battery technologies installed on board a Croatian purse seiner and trawler by using LCA, which offers insight into the environmental friendliness of the considered LiB's chemistry (LFP, NCA, NMC111, NMC532, NMC622, NMC811). This study deals with cradle-to-gate assessments, where the cradle refers to the resource extraction, and the gate refers to the output of a ship power system (tailpipe emissions). The functional unit is used to compare investigated power systems and, for this assessment, it is 1 kWh of the energy consumed. The system boundary is placed on the ship itself, where only emissions related to the ship's power system are investigated. This paper investigates emissions during the 20 years of the ship's lifetime, and they can be divided into three groups: Manufacturing (M), Well-to-Tank (WTT), and Tank-to-Wake (TTW) emissions. The first category encompasses emissions released from the manufacturing process of the primary component of a power system (engine, battery, etc.). The second category consists of WTT emissions, i.e., emissions released through the fuel cycle (processes of raw material extraction, fuel production, and distribution to the ship). The third category comprises emissions released during the ship's operation (TTW emissions). The overall life-cycle emissions, E_i (kg), are calculated by summing the emissions of particular gas i from each LCA phase (M, WTT and TTW phases) [39]:

$$E_i = E_{WTT,i} + E_{TTW,\,i} + E_{M,i}. \tag{7}$$

The LCA of the existing and alternative powering options is performed using LCA software GREET 2022 [42]. This software incorporates a comprehensive database comprising various fuels, stationary processes, and transportation processes associated with their life cycle. Although it is primarily intended for land transportation modes, GREET's processes of fuel application in a power system can easily be modified to describe ship power systems. In this paper, the impact categories of climate change, acidification and human toxicity are selected for analysis. They are investigated via the calculation of their

Global Warming Potential (*GWP* (kg CO_2-eq)), Acidification Potential (*AP* (kg SO_2-eq)) and Aerosol Formation Potential (*AFP* (kg PM2.5-eq)), according to the following equations [39]:

$$GWP = 1 \cdot E_{CO_2} + 36 \cdot E_{CH_4} + 298 \cdot E_{N_2O}, \tag{8}$$

$$AP = 1 \cdot E_{SOx} + 0.7 \cdot E_{NOx}, \tag{9}$$

$$AFP = 0.5 \cdot E_{PM10} + 0.54 \cdot E_{SOx} + 0.88 \cdot E_{NOx} \tag{10}$$

To investigate the profitability of alternative powering option, the LCCA is performed. The economic evaluation encompasses investment costs, fuel costs, and maintenance costs (covering the upkeep of the power system and equipment replacement), as well as a carbon tax applicable solely to power systems that generate tailpipe emissions, such as a diesel-powered ship in this instance.

Carbon tax refers to the purchase of permits for releasing each ton of CO_2 emissions (carbon allowance) into the atmosphere. Starting in 2024, the shipping sector will become part of the Emission Trading System (ETS), mandating that commercial cargo and passenger ships operating within the European Union whose GT exceeds 5000 tons must purchase carbon allowances [43]. In the past three years, the value of carbon allowance has gradually grown from around 20 EUR/t CO_2 to 95 EUR/t CO_2 [44], and it is projected to rise to 238 EUR/t CO_2 [45]. According to World Energy Outlook 2022 [46], there are three scenarios of projected carbon allowance, *CA* (EUR/t CO_2). The values of carbon allowances for each investigated carbon tax scenario can be found in a study carried out by Perčić et al. [39].

Carbon tax for the particular year is calculated by multiplying the annual CO_2 emissions from the TTW phase by a *CA* of a particular year. To ensure adaptation to additional costs, shipowners will pay for their reported emissions gradually, i.e., in 2025 for 40%, in 2026 for 70%, and from 2027, 100% of reported emissions [43].

The fuel costs usually represent more than 50% of the total costs of fishing vessels, e.g., trawlers 40–50% of their annual total costs, while for tropical tuna purse seiners, this cost exceeds 70% [33]. Recent fluctuance in fuel prices has greatly impacted the fishing sector, which represents an incentive for some alternative solutions.

2.2.1. The LCA and LCCA Models of a Diesel-Powered Ship

Before analyzing the electrification of fishing vessels with different batteries, the LCA and LCCA of the currently used powering option (diesel-powered ship) need to be performed, whose results serve as a baseline scenario. The energy needs of the diesel-powered purse seiner and trawler are presented in Section 2.1. The annual fuel consumption of diesel, FC_A (kg), is calculated with the following equation [20]:

$$FC_A = EC_A \cdot SFC, \tag{11}$$

where *SFC* (kg/kWh) represents the specific fuel consumption of diesel of 0.215 kg/kWh.

The conducted Life Cycle Assessment (LCA) for a diesel-powered ship takes into account emissions stemming from the engine manufacturing process (M phase), the crude oil recovery, its transportation to the refinery, the refining process, and fuel distribution to the pump (WTT phase), as well as the combustion of fuel during fishing activities (TTW phase), Figure 2.

Perčić et al. [20] evaluated the environmental impact of a diesel engine by determining the weight of each material. This is achieved by multiplying the weight ratios of the materials by the weight of the engine, denoted as m (t), calculated as follows:

$$m = \frac{2 \cdot P_{ave}}{450}. \tag{12}$$

The WTT phase involves crude oil extraction in the Middle East and transportation via a tanker covering a distance of 4000 km to Croatia. Upon reaching a Croatian refinery, the oil undergoes refining, and diesel is produced. Subsequently, it is distributed by a tank truck to the pump in the port, covering a distance of 100 km. The TTW phase relates to the combustion of diesel in the marine engine, leading to tailpipe emissions, denoted as E_{TTW} (kg), which are calculated by multiplying emissions factors, *EF* (g gas/kg fuel) by fuel consumption, *FC* (kg), with the following equation [39]:

$$E_{TTW} = EF \cdot FC, \quad (13)$$

where the *EF* for each gas (CO_2, CH_4, N_2O, NO_X, SO_X and PM) is obtained from the Fourth IMO GHG study [43] and presented in Table 3.

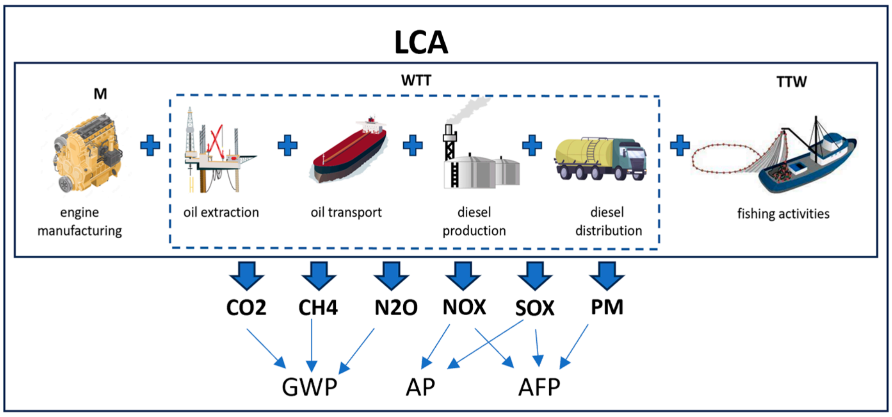

Figure 2. The LCA of a diesel-powered ship.

Table 3. Emission factors, *EF* (g gas/kg fuel) for diesel [43].

	***EF* (g gas/kg Fuel)**
CO_2	3206
CH_4	0.06
N_2O	0.15
NO_X	61.21
SO_X	2.64
PM	1.02

The LCCA of a diesel-powered ship includes investment, fuel, maintenance and carbon tax costs. The investment cost of an existing power system refers to the purchase of a new diesel engine, accounting for 250 EUR/kW [44], while the annual maintenance cost is 0.014 EUR/kWh [47]. Fuel cost calculation involves multiplying fuel consumption by the current diesel price. Considering recent fluctuations in fuel prices, the average price for European diesel is obtained from [48] and equals 0.84 EUR/kg. The carbon tax is calculated as described in Section 2.1, where the most rigorous scenario is taken into for the assessment.

2.2.2. The LCA and LCCA Models of an All-Electric Ship

Inputs required for LCA and LCCA are specific energy, lifetime and the price of a battery. The data found in the literature often vary in a very large range, which is also noted in the work of Hasselwander et al. [49]. They compared findings from the literature and expert interviews, and for their analysis on batteries applicable to electric vehicles, they took the variables presented in Table 4. These are used also in this paper.

Table 4. Required inputs for LCA and LCCA of an all-electric ship [49].

	Energy Density (Wh/kg)	Lifetime (Cycles)	Price (EUR/kWh)
LFP	185	3500	80
NCA	280	1000	90
NMC111	180	1500	145
NMC532	220	1200	130
NMC622	260	1200	100
NMC811	280	1000	90

It is assumed that the battery capacity must be sufficient to provide power for the entire duration of the fishing trip and it is calculated as follows [39]:

$$BC = 1.5 \cdot (P_{ME,ave} \cdot t_{ME} + P_{AE,ave} \cdot t_{AE}). \quad (14)$$

Battery capacity is increased by 50% due to maintaining the state of charge, safety and battery degradation. The energy needs of all-electric ship are equal to those for the existing diesel-powered ship.

The performed LCA of an all-electric ship considers emissions released from the battery manufacturing process (M phase) and electricity generation, transmission and distribution (WTT phase), as shown in Figure 3. Since the ship operates solely on batteries, there are no tailpipe emissions, i.e., TTW emissions are equal to zero.

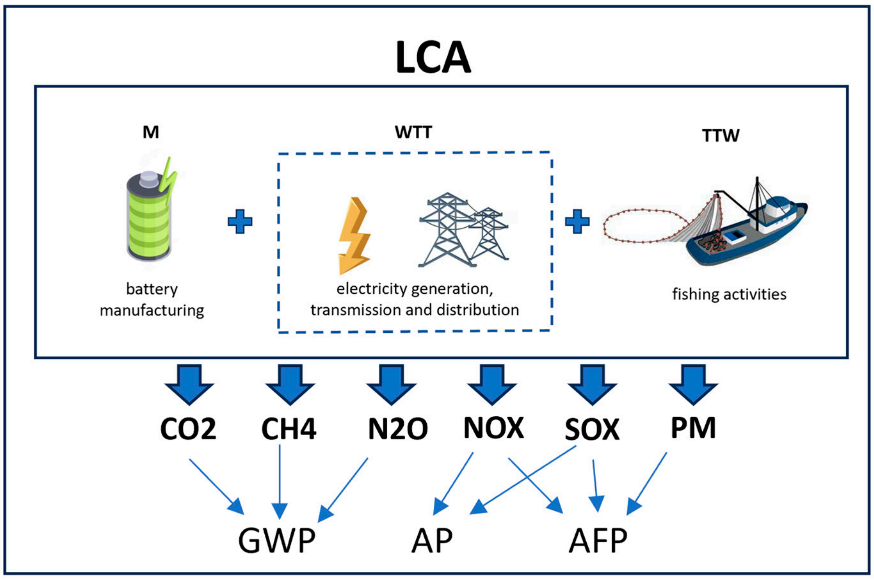

Figure 3. The LCA of an all-electric ship.

The environmental impact of the battery is assessed using GREET 2022 software, where battery weight represents an input. By dividing *BC* and battery energy density (Table 4), the battery weight is calculated. The battery is replaced after its lifetime, which is presented as a number of cycles of charging and discharging. During the 20 years of fishing operation, the battery would be charged 4000 times. By taking into account the lifetime for a specific LiB chemistry from Table 4, the number of replacements is calculated. The emissions released during electricity production depend on the electricity mix and in this paper, the European electricity mix is used, obtained from the GREET 2022 database, as shown in Figure 4.

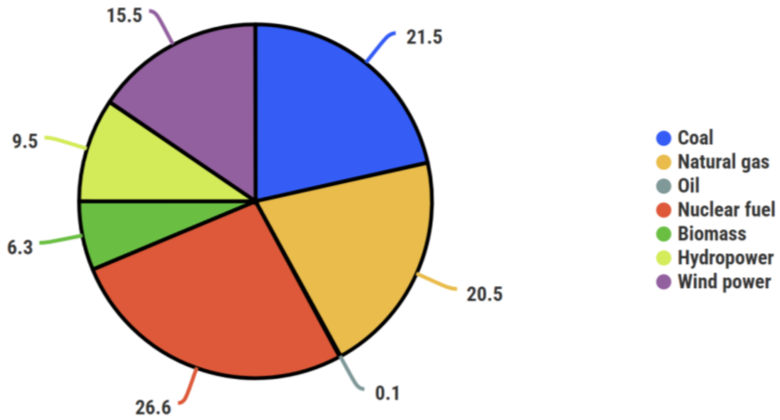

Figure 4. The European electricity mix.

The LCCA of an all-electric ship includes the investment cost, fuel cost, and maintenance cost, which also includes the battery replacement cost. The investment of a fully electrified ship refers to 45% of the battery cost, while 55% of the cost is attributed to additional equipment [20]. Battery cost is calculated by multiplying battery capacity by the battery price. The specific LiB's chemistry corresponds to a specific price, as shown in Table 4. It is assumed that once the battery needs to be replaced, the price of the battery declines by 25%. The maintenance represents 5% of the investment cost, while the fuel cost, i.e., electricity cost is calculated by multiplying the energy consumption by the electricity price. Due to fuel price fluctuations, the average electricity price is obtained from [6] and is equal to 0.04 EUR/kWh.

2.3. Limitations and Assumptions

The limitations and assumptions of this paper are listed as follows:

- The environmental and economic assessments are performed from the point of view of the shipping sector. The system boundary is defined around the ship, focusing solely on the power system during fishing activities. Other ship components, such as the hull, gear, crew, catch, port operations, etc., are not taken into consideration for LCA and LCCA. Due to that, the recycling processes of the main elements of a ship power system (i.e., diesel engine and battery) are not included in these assessments.
- Another limitation of this study is that the damaging effect of seawater on onboard batteries is not investigated.
- Bearing in mind fuel price fluctuations, fuel costs in LCCA are calculated using average diesel and electricity prices obtained from the literature.
- Within the LCCA, the costs are examined without calculating the net present value. Nonetheless, the LCCA remains effective in identifying the most cost-efficient power option.
- The analysis of LiB's chemistries investigated in this paper is limited to those found in the GREET 2022 database.
- In the literature, there can be found different data on battery prices. In this paper, the LCCA of an all-electric ship is performed using data from Hasselwander et al.'s work [49], presented in Table 4.
- In designing alternative power systems for marine applications, safety represents a very important issue. In this study, the safety aspects are not considered.

3. Results and Discussion

The environmental and economic performances of five different chemistries of LiBs are investigated. Each has a specific price, lifetime and energy density (Table 4) that are used to calculate their weight, cost and number of a replacement in a ship's lifetime. These results are presented in Table 5.

Table 5. Battery's particulars.

Vessel Type	*BC* (kWh)	Battery Type	Weight (t)	Cost (EUR mil.)	Number of Replacements
Purse seiner	4843	LFP	26.7	2.1	1
		NCA	17.3	1.6	4
		NMC111	26.9	3.9	2
		NMC532	22.0	2.7	3
		NMC622	18.6	1.9	3
		NMC811	17.3	1.6	4
Trawler	2340	LFP	12.6	1.01	1
		NCA	8.4	0.75	4
		NMC111	13.0	1.88	2
		NMC532	10.6	1.38	3
		NMC622	9.0	0.90	3
		NMC811	8.4	0.75	4

The LCA evaluates life-cycle emissions associated with ship power systems. The selected impact categories for analysis include climate change, human toxicity, and acidification. The results are presented in Figure 5 for the purse seiner and in Figure 6 for the trawler, where D denotes a diesel-powered ship.

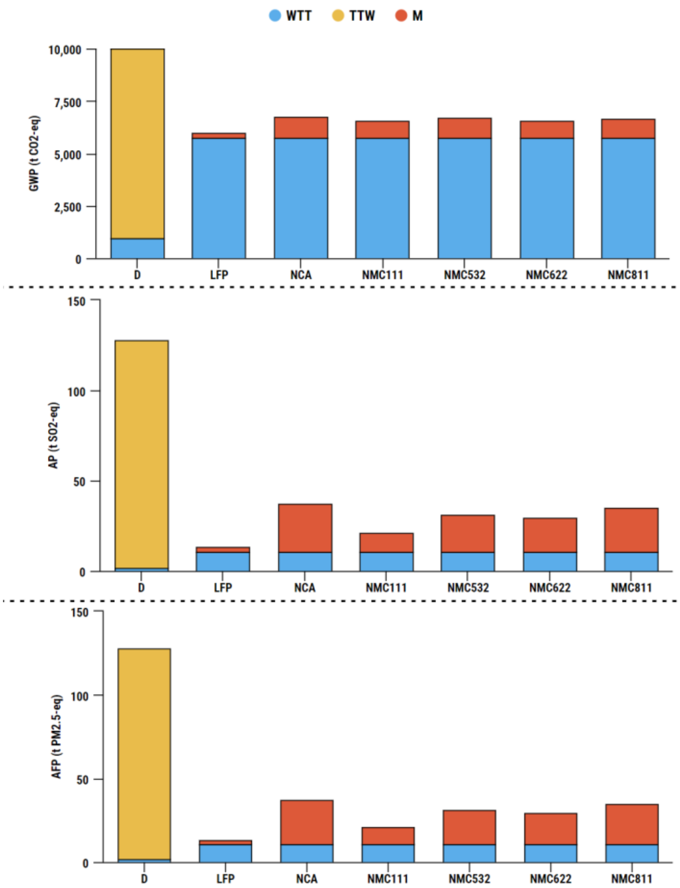

Figure 5. Environmental impact of the investigated powering options for the purse seiner.

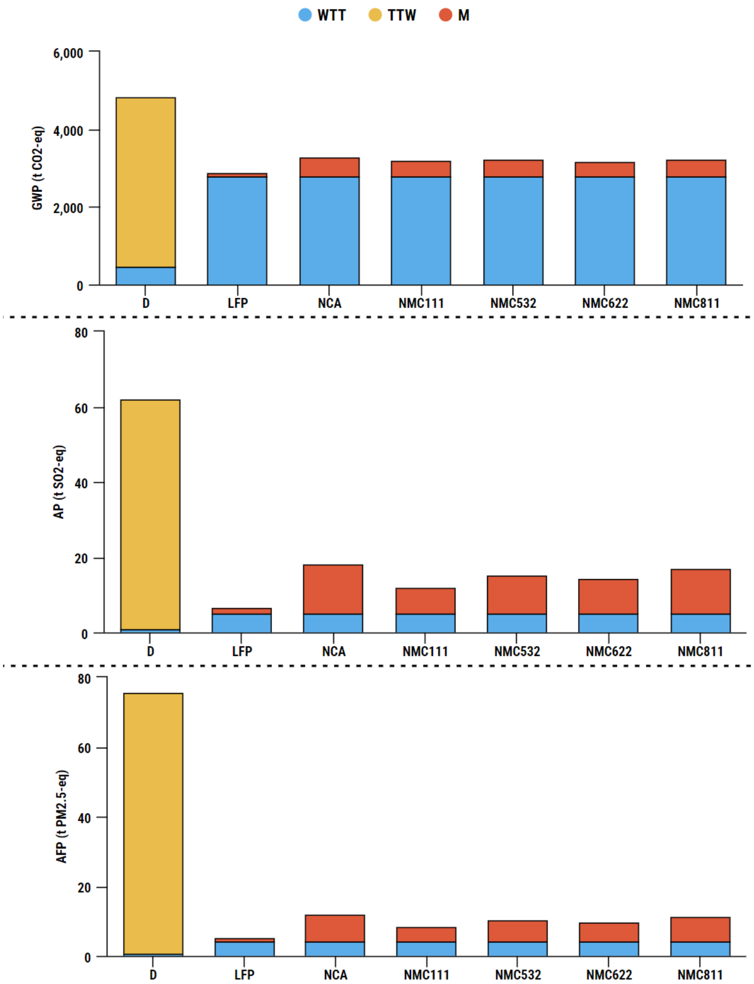

Figure 6. Environmental impact of the investigated powering options for the trawler.

The LCA results presented in Figures 5 and 6 indicated that each considered battery technology (battery chemistry) is environmentally friendlier than the existing powering option. It is mainly due to the high amount of TTW emissions released during the diesel combustion in an engine. LFP battery results in 40% lower life-cycle GHG emissions than those released by diesel-powered ship. Regarding the impact on acidification and human toxicity for both fishing vessels, the LCA results showed that the major contributor is the diesel-powered ship. Among the different batteries, the NCA and NMC811 batteries result in higher life-cycle emissions, mainly due to the number of replacements, i.e., they are replaced four times in a ship's lifetime.

To obtain insight into the profitability of replacing a diesel engine with a battery, the LCCA is performed. Besides investment, fuel and maintenance costs, the most rigorous scenario of a carbon tax is considered. The LCCA results are presented in Figure 7.

According to Figure 7, the existing powering option, i.e., a diesel-powered ship, results in the highest total costs, where fuel costs account for 60% of total costs. The LCCA results indicated that the LFP battery is not only the most environmentally friendly, but it is also the most cost-efficient battery. The reason for that is moderate energy density, low price of the battery and a long lifetime, which results in the replacement of the battery only once in a ship lifetime. The use of LFP on board the purse seiner results in 57% lower total costs, while on board the trawler, it results in around 53% lower costs. However, in this paper, the most rigorous carbon tax scenario is investigated. If the carbon tax is not included in the LCCA, only LFP would be a cost-efficient option, with around 35% lower total costs compared to the diesel-powered purse seiner and trawler.

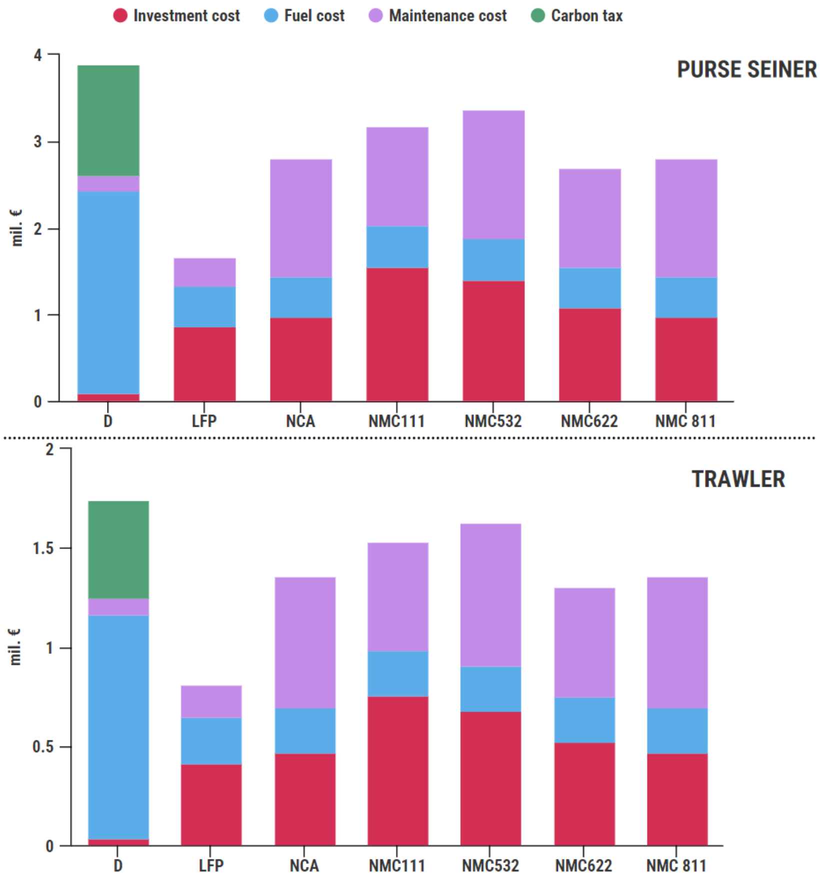

Figure 7. LCCA results.

Although this paper showed that the full electrification of considered fishing vessels is profitable for each battery chemistry without implementation of a very rigorous carbon tax scenario, further developments in battery technology would open the pathway towards electrification of other ships that operate on open seas. Already familiar battery technologies like LFP and NMC batteries will be developed in a sense of higher energy density and lifetime, but a lower price of the battery. One of the next-generation battery technologies is Solid-State Battery (SSB), in which an ion-conductive solid is used instead of a liquid electrolyte. These types of batteries are not flammable and have high energy density, but they are more expensive than those with liquid electrolytes, mainly due to the early stage of development. Further investigation into those batteries and their mass production in the future will reduce their price. Another future storage technology is a Sodium-ion Battery (SiB). It is considered a potential low-cost alternative to LiBs due to the wide availability of sodium. SiBs can be produced on the same line as LiBs. They are less flammable than LFP batteries and have moderate energy density [50].

To investigate the cost effectiveness of future battery technologies and their implementation on board, the LCCA is performed with data presented in Table 6. The results are presented in Figure 8, where the test case is the considered purse seiner.

Table 6. Future batteries and their specifications [50].

	Energy Density (Wh/kg)	Lifetime (Cycles)	Price (EUR/kWh)
LFP	220	5000	60
NMC	350	1500	70
SSB	400	500	150
SiB	200	3500	50

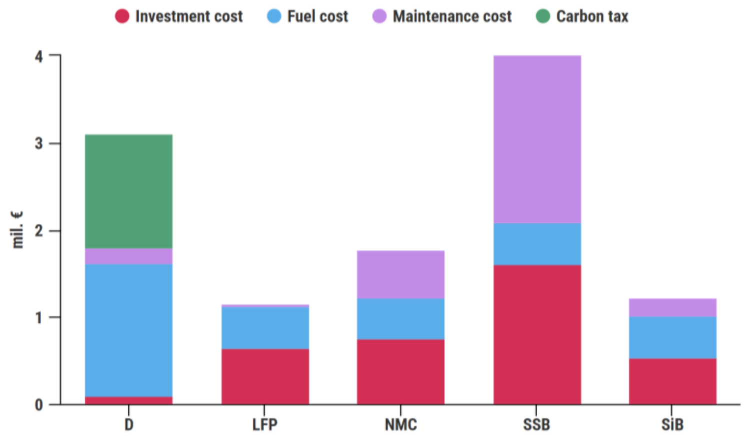

Figure 8. Cost comparison of diesel and future battery technologies.

The results presented in Figure 8 show that, in the future, the LFP battery and SiB would be suitable for the electrification of fishing vessels. The main reason why the cost of the SSB is high is the low lifetime, which results in high maintenance costs (SSB needs to be replaced eight times during the ship's lifetime).

4. Conclusions

This paper investigates the full electrification with different LiBs on board a Croatian purse seiner and trawler. To determine which battery satisfies the environmental and economic criteria, LCA and LCCA were performed. LCA investigated the environmental impact of power systems through three impact categories (climate change, acidification and human toxicity), while LCCA included investment cost, fuel cost, maintenance cost and carbon tax. The LCA and LCCA results of alternative power system configurations are compared with the diesel power system configuration, which serves as a baseline. The main findings of the research can be summarized as follows:

- The LCA comparisons for each impact category indicated that the most environmentally friendly option is the LFP battery, while the second alternative with the lowest emissions is NMC111. Each considered all-electric ship results in lower emissions compared to a diesel-powered ship. LFP on board a purse seiner and trawler results in around 40% lower GHGs. Among the considered batteries, NCA and NMC811 result in the highest environmental footprint mainly due to the high number of their replacement during the 20 years of the ships' lifetimes.
- The LCCA comparison indicated each all-electric ship's results in lower total costs compared to a diesel-powered ship. The most cost-efficient battery is LFP, resulting in 57% lower costs (for purse seiner) and 53% lower costs (for trawler) compared to the diesel power system configuration. If the carbon tax is not considered within LCCA, LFP would be the only option with lower costs than a diesel-powered ship.
- The profitability of the full electrification of ships is highly dependent on the market, i.e., battery prices. With the ones used in this study, the full electrification of fishing vessels represents an appropriate replacement for diesel–mechanical propulsion. Both environmental and economic assessments indicated the LFP battery as the most feasible battery for the all-electric purse seiner and trawler operating in the Adriatic Sea.

Further research will concentrate on diverse hybrid power systems suitable for implementation in Croatian fishing vessels. More advanced solutions for a ship's power system that can effectively meet the necessary emission reduction goals while maintaining reasonable costs are going to be investigated.

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Nomenclature

Variables	
AFP	aerosol formation potential (t PM 2,5 -eq)
AP	acidification potential (t SO_2-eq)
BC	battery capacity (kWh)
CA	carbon allowance (EUR/t CO_2)
E	emission (t)
EC	energy consumption (kWh)
EF	emission factor (g emission/kg)
FC	fuel consumption (kg)
GWP	global warming potential (t CO_2-eq)
m	weight of an engine/t)
P	power (kW)
SFC	specific fuel consumption (kg/kWh)
t	time (h)
Subscripts	
A	annual
AE	auxiliary engine
ave	average
i	gas
ME	main engine
PS	purse seiner
T	trawler
Abbreviations	
CII	Carbon Intensity Indicator
D	Diesel
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
ETS	Emission Trading System
GHG	Greenhouse Gas
GT	Gross Tonnage
HFO	Heavy Fuel Oil
HPS	Hybrid Power System
IES	Isolated Energy System
IMO	International Maritime Organization
LCA	Life-Cycle Assessment
LCCA	Life-Cycle Cost Assessment
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LiB	Lithium-ion Battery
LMO	Lithium Manganese Oxide
LTO	Lithium Titanium Oxide

M	Manufacturing
MDO	Marine Diesel Oil
NCA	Lithium Nickel Cobalt Aluminum Oxide
Ni-MH	Nickel-Metal Hydride
NMC	Lithium Nickel Manganese Cobalt oxide
Pb-acid	Lead-acid
PM	Particulate Matter
SEEMP	Ship Energy Efficiency Management Plan
SiB	Sodium-ion Battery
SSB	Solid-State Battery
TTW	Tank-to-Wake
WTT	Well-to-Tank

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