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Environmental and economic assessment of electric ferries with different lithium-ion battery technologies

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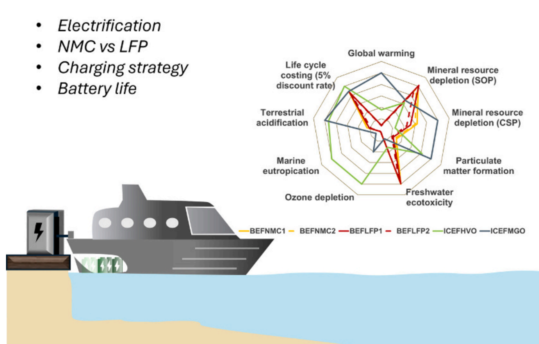
HIGHLIGHTS

- Holistic cradle-to-grave comparison of NMC and LFP battery types by considering factors like DoD, ferry design, supply chain of battery, battery lifetime considering degradation factors
- The impact of weight changes due to installation of battery on the operation profile is included in the assessment
- Assessment of different charging strategies including the life cycle inventory of charger production. Result shows that extended opportunity charging intervals reduces environmental impacts further, as they reduce the installed battery capacity, and this also indirectly saves energy due to the reduced weight.
- Cost assessment with different discount rates. Scenario analysis and sensitivity analysis on different parameters.

GRAPHICAL ABSTRACT



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ABSTRACT

Electrification of passenger ferries is an important strategy for reducing the emission of greenhouse gases and air pollutants from domestic shipping. Although several battery electric ferries are currently operational, there is still a lack of information on how different lithium-ion battery chemistries and sizing will affect environmental impact and overall cost competitiveness. This study compares the environmental impact and economic performance of using varying charging strategies for two different battery types (defined by the active material of the positive electrode – lithium nickel manganese cobalt oxide or lithium iron phosphate) for electric ferries using life cycle assessment and life cycle costing. The results demonstrate that, compared to conventional marine gas oil-powered ferries, fully electric ferries offer more than 90 % reduction in contributions to climate change, while biodiesel offers around 65 % reduction. This is despite the fact that the production of batteries and other electric powertrain components causes an increase in greenhouse gas emissions from ferry manufacturing, compared to the marine gas oil ferry option. Battery electric ferries also significantly reduce other impacts like acidification

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(−75 %), marine eutrophication (−65 %), particulate matter formation (−70 %), and ozone depletion (−90 %) over the life cycle; however, there is an increase in environmental impact related to resource utilization (1.2 to 1.5 times) and ecotoxicity (8–9 times). Comparing the two battery alternatives assessed, lithium iron phosphate batteries are preferable both in terms of life cycle environmental impact and cost competitiveness. Extended opportunity charging intervals can reduce environmental impacts further, as they reduce the installed battery capacity, and this also indirectly saves energy due to the reduced ship weight. Carbon abatement cost is around 100€/tCO2eq. A lower interest rate on capital investment in a battery electric ferry brings the carbon abatement cost below zero. This finding indicates that battery electric ferries can be cost-competitive with fossil fuel alternatives with policy support.

1. Introduction

Full electrification of ships offers a path to zero-emissions during operation, eliminating greenhouse gases and air pollutants like nitrogen oxide (NOx), sulfur oxide (SOx), and particulate matter (PM). Shipping segments that are suitable to electrify with batteries as energy storage are those operating on short and regular routes, for example, passenger ferries and service ships. Since the launch of the first fully electric ferry "Ampere" in 2015 [1], there are more than 800 all-electric or hybrid ships currently in service worldwide [2]. Even though fully battery electric ferries (BEFs) have higher energy efficiency and cleaner operation, batteries have an environmental impact associated with their production. Additionally, the electricity mix used for charging is also associated with environmental impact. Adding to these impacts, the battery and electricity costs are also important for the total cost.

One factor affecting the operational pattern of a BEF is the availability of charging stations and the expected frequency of charging. It is crucial for the requirement of onboard energy storage capacity and can limit the feasibility of fully electric operation [3]. The charging strategy plays a significant role in determining the battery size and the charging cycles, which directly impact battery life [4]. For example, automated charging systems can charge BEFs multiple times a day in the form of "opportunity charging", i.e. charging while the ferry is at the dock allowing passengers to embark and debark.

Another important factor in the design of the BEF is the choice of battery chemistry. Different battery chemistries have different characteristics like energy density, cycle life, the internal electrical resistance of the pack, and specific power, which all will influence the sizing and thereby the energy consumption of the ferry itself. Referring to the selection of the positive electrode active materials (i.e., the cathode when operating in discharge mode), two common types of lithium-ion battery (LIB) chemistries widely used in marine applications are lithium iron phosphate (LFP) and lithium nickel manganese cobalt oxide (NMC) [5]. These are both typically combined with graphite as the active material for the negative electrode (i.e., the anode). The NMC type offers a higher energy density [6], resulting in a lighter vessel and a shallower draught compared to LFP type. A deep draught gives large hull resistance, and thus more power and energy are required for the same operational speed. In addition, the choice of cell format (such as pouch, cylindrical, or prismatic), packaging, and thermal management also impact battery pack energy density and in turn, influence the weight of the total battery pack [7]. The downside of NMC is that it has a shorter cycle life compared to LFP [8], which results in more battery pack replacements over the BEFs lifetime.

The battery cycle life is highly linked to the user profile, and by using a smaller "depth of discharge" (DoD) the lifetime can be extended. The DoD is defined as the capacity discharged from a battery that is fully charged, divided by the battery's nominal capacity. Another common measure is the "state of charge" (SOC), defined as the ratio of available capacity over the maximum capacity that can be stored in the battery. 100 % SOC means a fully charged battery and 0 % SOC means a fully discharged battery. Using a battery between 100 and 0 % SOC corresponds to 100 % DoD, and 100–50 % SOC equals 50 % DoD. By limiting the upper SOC level, i.e., not allowing it to become fully charged, further lifetime gain can be achieved [9].

A holistic comparison of BEFs can be expected to consider a combination of these presented factors, such as the electricity sources used for charging, the specific battery technology chosen, battery lifetime, the supply chain of battery production, and the strategies employed for charging. Presently, there is a lack of knowledge of how these factors affect the cost and environmental impacts over the life cycle of a fully electric ship. This study aims to fill this gap by evaluating and comparing the economic performance and environmental impact of different BEF designs for a case study ferry, considering two different battery chemistries and charging strategies over the entire life cycle (cradle-to-grave) of the ship. These results are also compared with a corresponding ferry operating on either biodiesel or fossil marine gas oil (MGO). A literature review that assesses the existing understanding of the environmental performance of battery electric (BE) ships, complements the case study. This review covers the overview of system boundaries considered, transparency and availability of inventory data, selection of battery types, and parameters influencing assessment.

2. Literature review

To identify existing LCA studies of battery electric ships, a comprehensive search was conducted in the Scopus database, using specific search phrases in titles, abstracts, and keywords. The search employed a three-part approach. First, it identified studies mentioning LCA using terms like "LCA," "environmental assessment," or "life cycle assessment". Second, it focused on ships by including terms like "ship*," "marine," "maritime," or "ferry". Finally, it narrowed down the results to battery-powered ships by incorporating the term "batter*." The search resulted in 73 publications issued until December 2023. Further use of "snowballing", i.e., scanning the reference lists of the already identified papers, yielded no additional results. The complete set of found publications were then screened to decide on a final set for inclusion in the review. Only those considering maritime transport and including a fully battery electric ship case were included. Those considering only hybrid or fuel-cell electric options were excluded. Two relevant conference papers were also excluded since they were almost identical to two of the journal articles found. In total 13 publications were found relevant for analysis in this review and all of them have been published after 2020.

Table 1 summarizes the key elements used in the selected publications including system boundaries, electricity considered for charging, battery and ship detail, inventory data source, and main results. Based on their scope, these studies can be divided into three categories. The first category of studies refers to LCAs that include only "well-to-wake" (WTW) assessments, i.e., omitting the impact of producing the propulsion system, the batteries, and other parts of the ship. Five studies (Jeong, et al. [10] Jeong, et al. [11] Perčić, et al. [12] Park, et al. [13], Park, et al. [14], and Vakili and Ölçer [15]) fall into this category and these studies focus on scenarios for the charging electricity, "well-to-tank" (WTT), and how efficiently this energy is used for propulsion, "tank-to-wake" (TTW).

The second category of studies are LCAs with life cycle scope including both the WTW energy use and the battery life cycle

Table 1
Overview of the reviewed studies: comparing scopes, electricity mix, inventories, battery technology, technology life, and main result. Abbreviations: WTT - Well to Tank, TTW - Tank to Wake, DoD - depth of discharge, NA - not available, y - years, NCA - lithium nickel cobalt aluminum oxide, PbA - lead acid, NiMH - nickel-metal hydride, LFP - lithium iron phosphate, and NMC - lithium nickel manganese cobalt oxide.

Study	Scope/system boundary	Charging electricity mix	Inventory	Battery type/ format	Battery life/ Ship life	Environmental impacts	Ship type/ charging/ DoD	Reported GHG emissions
Perčić, et al. [16] (2020)	WTT, TTW, and battery production	Croatian electricity mix	GREET 2018	Type: NA Format: NA	Battery: 10 y Ship: 20 y 1 replacement	GHG emissions	Ship: RoPax Charging: round trip DoD: NA	RoPax: 27.92 $kgCO_{2eq}$/nm
Jeong, et al. [10] (2020)	WTT and TTW	Six scenarios: coal, oil, natural gas, wind, hydro and nuclear.	GaBi 2019	Type: NA Format: NA	Battery: NA Ship: 30 y	GWP, Acidification, Eutrophication, Photochemical ozone creation (CML 2001)	Ship: RoPax Charging: round trip DoD: 50 %	9.24×10^5 1.76×10^7 kgCO2eq/ship life
Perčić, et al. [17] (2021)	WTT, TTW, and battery production	Croatian electricity mix	GREET 2020	Type: NA Format: NA	Battery: 10 y Ship: 20 y 1 replacement	GHG, NO_X, SO_X, and PM_{10}	Ships: Cargo ship, passenger ship, dredger Charging: round trip; DoD: 75 %	Cargo ship: 3800 tCO_2eq/lifetime Passenger: 1200 tCO_2eq/ lifetime Dredger: 1500 tCO_2eq/ lifetime
Wang, et al. [18] (2021)	WTT, TTW, and battery production	UK grid mix 2050	Inventory from literature and GaBi 2018	Type: NMC Format: NA	Battery: 10 y Ship: 30 y 2 replacements	GWP (CML 2001)	Ships: Ferries/650 kWh Charging: round trip DoD: 70 %	NA
Fan, et al. [19] (2021)	WTT, TTW, and battery production	Chinese grid mix	GREET 2018	Type: NA Format: NA	Battery: 10 y Ship: 30 y 2 replacements	CO_2 emissions	Ships: Container/ 2160 kWh Charging: 4 per trip DoD: 80 %	Container: 6018.54/ lifetime
Kanchiralla, et al. [20] (2022)	WTT, TTW, and battery and powertrain production	Swedish and German grid mix 2030	Inventory from literature and Ecoinvent 3.7	Type: NMC811 Format: NA	Battery: 12 y Ship: 25 y 2 replacements	GWP and 10 other environmental impacts (EF 3.0)	Ship: RoPax Charging: every round trip DoD: 70 %	RoPax: 57 tCO_2eq/ round trip
Jeong, et al. [11] (2022)	WTT and TTW	Electricity grid mix of 27 different nations	GaBi 2020	Type: NA Format: NA	Battery: NA Ship: 45 y	GWP, Acidification, Eutrophication, Photochemical ozone creation (CML 2001)	Ship: Ferry fleet Charging: every round trip DoD: 70 %	6.83×10^{-3} to 1.88 kgCO2eq/kWh
Perčić, et al. [12] (2022)	WTT, TTW, and battery production	European electricity mix	GREET 2020	Type: PbA, NiMH, NMC Format: NA	Battery: varies Ship: 20 y Replacements: PbA- 32, NiMH- 16, NMC-3	CO_2, NO_X and SO_X emissions	Ship: RoPax1/ 280 kWh RoPax2/ 2490 kWh RoPax3/ 8990 kWh Charging: trip; DoD: 80 %	RoPax1: 2500–2800 tCO_2/ lifetime RoPax2: 21000–25,000 tCO_2/ lifetime RoPax3: 75000–80,000 tCO_2/ lifetime
Park, et al. [13] (2022)	WTT and TTW	Electricity grid mix of 27 different nations	GaBi 2020	Type: NA Format: NA	Battery: NA Ship: NA	GWP, Acidification, Eutrophication, Photochemical ozone creation (CML 2001)	Ship: RoPax Charging: every round trip DoD: 50 %	Ferry fleet: different values for 29 nations
Park, et al. [14] (2022)	WTT and TTW	UK electricity mix	GaBi _	Type: NA Format: NA	Battery: NA Ship: NA	GHG emissions	Ship: Ferries Charging: NA; DoD: NA	0.25kgCO2eq/kWh
Vakili and Ölçer [15] (2023)	WTT and TTW	Six scenarios: Coal, natural gas, wind, hydro and heavy oil	GaBi 2020	Type: NA Format: NA	Battery: NA Ship: 25 y	GHG emissions	Ship: RoPax, 1570 kWh Charging: trip	0.37 to 63.62 kgCO2eq./nm
Guven and Ozgur Kayalica [22] (2023)	WTT, TTW, and battery and powertrain production	Turkey electricty mix	GREET 2021	Type: NMC811, NMC622, LFP, NMC532,& NCA Format: NA	Battery: 10 y Ship: 35 y 2 replacements	GWP, NOx, SOx and PM emissions, and energy and water consumption	Ship: Ferry 5387.5 kWh Charging: DoD: 80 %	~23,000 tCO2eq/ lifetime for all battery types with the lowest for LFP

(continued on next page)

[12,16–22], but not the rest of the ship. Percic and colleagues performed three LCA studies, one considering the operation of Ropax ships in Croatia [16], a second one on a Cargo ship, a passenger ship, and a dredger in Croatia [17], and a third on RoPax ships operating in Croatia but comparing an NMC type battery with lead acid (PbA) and nickel-metal hydride (NiMH) options [12]. These studies do not specify the specific composition of the cathode chemistry used in LIB or any details about the format. Their inventory data is based on different versions of GREET [23]. A battery life of 10 years is uniformly considered in the three studies [12,16,17]. The electricity mixes studied include the Croatian electricity supply mix and the average European electricity supply mix. In another study, Wang, et al. [18] also included the battery life cycle in the assessment of ferries operating in the UK, while considering a future, projected UK grid mix of 2050. This study compiled its battery data from literature and used GaBi 2018 [24] for background data. An NMC battery with a 10-year-life is considered, but the battery cell format or pack details are not mentioned. In the study by Fan, et al. [19], the assessment is performed for an inland container ship operating in China using an average Chinese electricity mix. The battery data is based on GREET 2018, but the study does not specify the chemistry or the cell format. The battery life is considered to be 10 years, resulting in two replacements during the ship life.

The third category, for which three studies were found, incorporates those that have conducted LCA of the life cycle of other powertrain components as well as the battery, along with the WTW stage. A specific composition of the NMC type battery (NMC 811) is used in two studies by Kanchiralla and colleagues [20,21], and these assessments used battery production data from literature [25,26], in combination with Ecoinvent 3.7 for the background processes. The battery cell format and pack designs are not mentioned in these studies, however, a battery life of 12 years based on DoD 70 % is considered for the batteries. A RoPax ship traveling between Sweden and Germany charging with Swedish and German electricity mixes in respective ports is considered in the first study [20]. In the other study [21], the EU 2030 electricity mix is considered for the operation of a service ship and a RoPax ship. In addition to the battery, the electric motor life cycle is included in both these studies. Also, in this category, Guven and Ozgur Kayalica [22] made a comprehensive LCA of a passenger ferry operating in Bosporus, when equipped with different types of LIBs including several NMC versions (NMC 532, NMC 622, and NMC 811), lithium nickel –cobalt aluminum oxide, and LFP. A battery life of 10 years with two replacements is uniformly considered for all battery types, but the battery format is not mentioned. The electricity charged for the ship operation is assumed as Turkish electricity mix.

There are many modeling gaps in this body of literature. Only one of the studies in the third category includes other ship parts than the powertrain components and batteries in the assessment, Kanchiralla et al. [20,21]. Also, all studies assume battery sizes based on simplified assumptions for a single route for operation. However, often the battery pack sizing will depend on charging parameters (like power, time, frequency, etc.) along with operational parameters (like discharge rate, operational speed, route, etc.). Another aspect not covered in any of the studies found is the change in the ship's operational energy due to changes in the net weight of the ship. The weight of a BEF would be different from an otherwise identical internal combustion engine-based ferry (ICEF), meaning that the electrification would modify the operational draught and energy [27]. Another real-world design parameter not considered in these earlier studies is the choice of DoD or SOC interval and their strong linkage to the battery lifetime [4]. The studies included in the literature review also use simplified data for battery pack production and do not make use of the extensive data for inventory analysis, which has become available in recent years (e.g. [26,28–31]). Furthermore, a final important aspect omitted in all mentioned studies is the impact of the infrastructure required for charging the BEFs.

3. Materials and methods

The economic and environmental assessment is carried out on a specific case study ferry, further described in section 3.1. The functional unit of the study is set as "annual operation of the ferry" which is around 5300 h per year. This ensures consistency in comparing included ferry options by accounting for variation in energy demand due to: (1) weight differences between BEFs with different battery installations and with ICEFs; (2) efficiency differences between powertrain components used in different options; (3) shifts in the time schedule based on the season, and linked propeller load variation based on changes in weather conditions; and (4) the availability of excess heat from engines and the inclusion of alternative heat sources in BEFs to match the varying heat demand over different seasons.

The assessment is conducted for four BEF options, i.e., electric versions of the case study ferry, modeled differently in terms of battery cell technology (NMC622|graphite or LFP|graphite) and two alternative charging strategies, and two ICEF options, i.e., conventional versions of the case study ferry, fueled alternatively with hydrotreated vegetable oil (HVO), a biofuel, or marine gas oil (MGO), a fossil fuel. In total, this gives six studied options:

1) BEFNMC1 – BEF with NMC622|graphite battery cells, combined with the first charging strategy
2) BEFNMC2 – BEF with NMC622|graphite battery cells, combined with the second charging strategy
3) BEFLFP1 – BEF with LFP|graphite battery cells, combined with the first charging strategy
4) BEFLFP2 – BEF with LFP|graphite battery cells, combined with the second charging strategy
5) ICEFHVO – ICEF fueled with HVO
6) ICEFMGO – ICEF fueled with MGO

The two charging strategies differ in the time allowed for charging at the most energy-consuming part of the operation. With the same charging power, a longer charging time allows it to reach a higher SOC, and hence charging time is one of the aspects considered while dimensioning the battery (more details in Section 3.1). Differing from the previous studies presented in chapter 2, all studied options 1–6 take the hull and the superstructure of the ferry into account, albeit in a generic approach. The environmental assessment adopts an attributional approach, using average data for inventory analysis, assuming that the ferry is constructed in 2025 and commences operations in 2026. A ferry has a long service life and 40 years is assumed for this study. This means that the vessel will operate until 2065. However, during this period the

Table 1 (*continued*)

Study	Scope/system boundary	Charging electricity mix	Inventory	Battery type/ format	Battery life/ Ship life	Environmental impacts	Ship type/ charging/ DoD	Reported GHG emissions
Kanchiralla, et al. [21] (2023)	WTT, TTW, and battery and powertrain production	Wind power and EU electricity mix 2030	Inventory from Literature and Ecoinvent 3.7	Type: NMC811 Format: NA	Battery: 12 y RoPax: 25 y/ 2 replacements Service ship: 40 y/ 3 replacements	GWP and 10 other environmental impacts (EF 3.0)	Ships: RoPax, service ship Charging: round trip DoD: 70 %	Ropax: 1.3–2 gCO_2eq/GTkm Service ship: 36.0–43.5 gCO_2eq/ GTkm

electricity supply mix is expected to change. For this reason, projected average electricity supply mixes for Sweden, over the time span from 2025 to 2065, are used for the use phase assessment, both for a base case scenario and two alternative scenarios. The study also explores how results are affected by a scenario for second-life use of the battery packs.

3.1. Scope

In this section, the case study ferry, the technical details of the powertrain, and the system boundary used in the life cycle assessment and costing are presented.

Case study ferry: The case study ferry template is a real-world passenger ferry that operates in the southern archipelago of Gothenburg in Sweden. It is used for public transport to and from the mainland and connects various islands within the archipelago. The ferry operates all year-round on a timetable that varies between weekdays and weekends. During the day, the ferry navigates between three docks on the mainland (Saltholmen, Lindholmen, and Stenpiren) and 12 other docks on different islands. The operational route is shown in Fig. 1. At night, the ferry docks at Donsö island.

The hull of the ferry is made of steel having an ice class rating allowing it to operate during winter conditions. It has a conventional powertrain setup and is propelled using two 440 kW Volvo Penta D16-MH 600 diesel engines and a controllable pitch propeller via a co-driving gear [32]. More technical and operation details are given in Table 2. The data was collected from the operator (from the stability book, general arrangement drawings, and interviews) and the IHS database. The fuel consumption data was derived from this primary data. Due to NOx regulation, the ferry is installed with a selective catalytic reduction (SCR) unit and a urea tank. The technical and operational details utilized for the ICEFHVO and ICEFMGO cases studied are the same and directly based on the selected real-world ferry.

BEF design: The powertrains of the BEF options vary significantly and have different overall weights depending on the battery type and size. Otherwise, the modeling keeps the same operational details and general design of the case ferry, also for the BEFs. For propulsion, the same controllable pitch propeller and gearbox are considered, however, instead powered by two 450 kW (output) permanent magnet synchronous electric motors (PMSM). To deliver the power and voltage required for the motors from the batteries, six sets of 150 kW inverters (dc-ac) are assumed. For the space heating requirement, instead of the heat pump (25 kW), boilers (155 kW), and waste heat recovery units present in the

Table 2
Key data and parameters of the original case study ferry, including technical and operational details.

General details of the ferry			
Light Dead Weight (LDT)	212 t	Service speed	13.5 knots
Length x Breadth	34.4 mx 7.8 m	Passenger capacity	450
Dead Weight Tonnage (DWT)	64.8	Max Draught	2.74
Propeller	KaMeWa controllable pitch propeller	NOx regulation	Tier III
Technical and operation details			
Main engines (ME)	2 sets, Penta D16 MH, total 882 kW	Diesel tank volume	16,000 l
Auxiliary engines (AE)	2 sets, Perkins 4.4TWGM, total 60 kW	Heat pump	25 kW
NOx abatement	Selective Catalytic Reduction	Boiler	155 kW
Annual fuel consumption (ME)	*228,300 kg*	Annual fuel consumption (AE)	*13,350 kg*
Bunkering frequency	Once in two weeks	Annual fuel consumption (Boiler)	*29,750 kg*

ICEF options, the BEFs carry heat pumps with a total output of 300 kW (as engine waste heat is not available). As BEFs do not need auxiliary generators, SCR units, urea tanks, daily tanks, or exhaust systems, these components are assumed to be removed, giving more room for batteries. To keep the requirements on the battery size down, high power opportunity charging at the two mainland stops Saltholmen and Stenpiren is considered using an automated fast charger with 4 MW. A 0.5 MW charger is considered for the overnight charging at Donsö.

In this setup, the total usable energy required from the battery is determined by the most energy-consuming segment of the route. This segment starts after a 2.5-h-stay at Saltholmen and the ferry goes between various islands down to the southernmost stop at Vrångö, before it returns to Saltholmen, now for a 10 or 20-min stop. The ferry then repeats the route down to Vrångö and comes back up to Saltholmen, but this time only for a 2-min stop before it goes inland up the river Göta Älv to Stenpiren, where it stops for around 50 min. The two charging strategies applied in the study differ in terms of the time available for charging at Saltholmen after the first of the two roundtrips. In strategy 1,

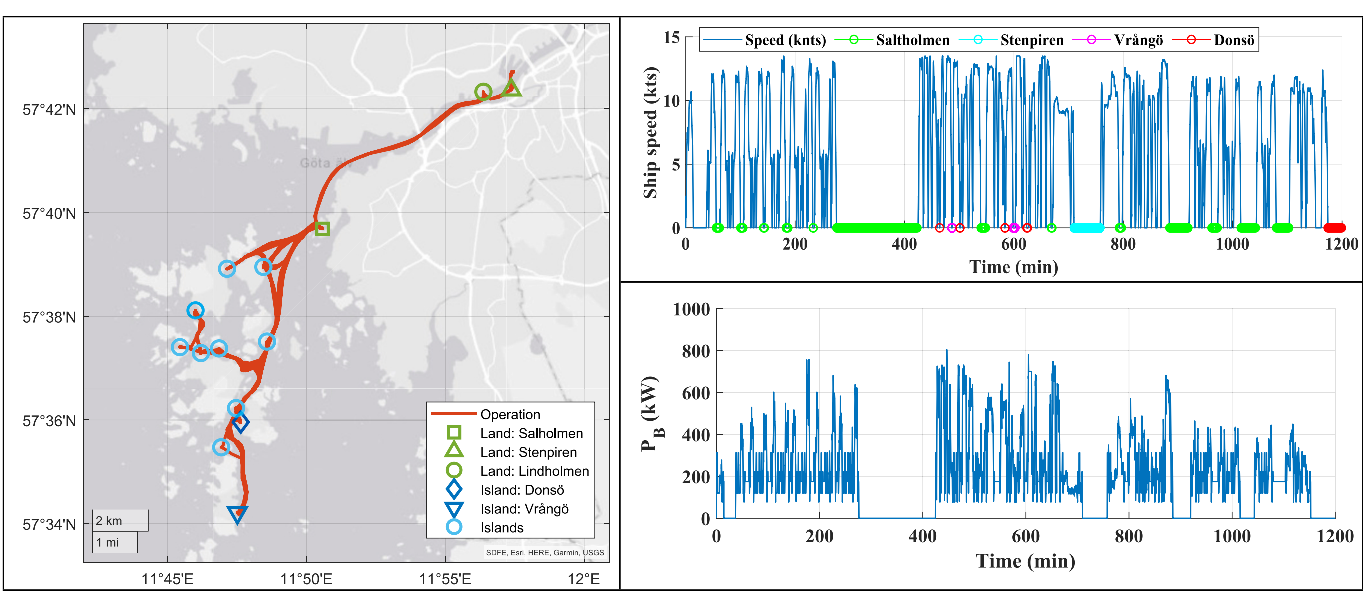

Fig. 1. Operation of case study vessel. A.) Route during 4 days in autumn, B.) speed in the selected route, C.) Brake power.

the available time for charging is about 10 min (as in the original timetable) and in strategy 2, the duration of the stop is extended to 20 min. With this 10 min extension of charging time once during this critical route lead to 33 % of reduction of the installed battery capacity (Table 3).

On top of the energy demanded to propel the ferry over the most energy-consuming segment, the total required usable battery capacity is calculated also accounting for other onboard energy demand (auxiliary systems, heat), losses due to varying efficiency in different powertrain components (power converters, motors, shafts, propeller), and the internal electrical resistance of the battery pack. In addition, a sea margin of 15 % is added to ensure operation during rough weather. LFP and NMC have different energy densities meaning that the weight of the battery system, and thus the total weight of the ferry differs for each BEF case. This also implies that the ferries display differences in draught, i.e., the depth of the ferry below the waterline. In turn, this changes the hull resistance, such that a deeper draught requires more propeller power for the same speed. The resulting difference in energy use due to the weight variation is calculated using Holtrop-Mennen's (HM) method. For this energy use calculation, it is also assumed that the ferry is loaded with 50 % pax capacity on average during the operation over the year. The details of these calculations are presented in the Electronic Supplementary Information (ESI) section 1.1. Adding to this, the total installed energy storage capacity of a battery is typically not allowed to be used in any application as this will result in too high aging of the battery. In this work the lower and upper SOC levels are assumed to be set at 15 % and 85 % respectively, giving a usable SOC interval (and a usable DoD) corresponding to 70 % of the installed nominal capacity for all options. A summary of the nominal data for key components in all BEF options is given in Table 3. It can be noted that when compared at full load, all BEFs are lighter than the ICEF for the case when its fuel tank is full.

Life cycle scope: Fig. 2 shows the life cycle scope system boundary used in the study, including the equipment life cycle stages of the ferry and fuel life cycle from well-to-wake (WTW). The equipment life cycle of a ferry involves the construction of the hull and superstructure, as well as the production of powertrains, including the batteries. In the study, it is assumed that all parts of the ferry are built in Europe. Additionally, some components need to be replaced if their lifespan is shorter than that of the complete ferry. This is covered in the study in the case of batteries and engines. However, end-of-life treatment (EoL) is not included beyond the use of recycled content brought in as secondary input in upstream materials processing, in line with a cut-off modeling approach when separating different product life cycles. The EoL stage of a product typically includes collection, several steps of disaggregation, and different forms of material recycling. In essence, this study instead cut-off the life cycle directly after the use phase, based on the argument that the EoL otherwise will introduce additional large scenario uncertainty given the long use phase of the ferries. Recycling and EoL treatment of batteries and powertrain components is currently under rapid development and can be expected to change significantly over the course of time up to and near after 2065, during which the EoL treatment will take place, at different points in time for replacement parts and the rest of the ferry options.

Table 3
Key component design specifications included in the assessment for the four BEF options.
FCE – full cycle equivalent; DoD – depth of discharge.

	BEFNMC1	BEFNMC2	BEFLFP1	BEFLFP2
Electric motor	2 sets, 450 kW	2 sets, 450 kW	2 sets, 450 kW	2 sets, 450 kW
Auxiliary unit	*60-kW, 50 Hz*	*60-kW, 50 Hz*	*60-kW, 50 Hz*	*60-kW, 50 Hz*
Invertors	6 sets, 150 kW	6 sets, 150 kW	6 sets, 150 kW	6 sets, 150 kW
Heat pump	300 kW	300 kW	300 kW	300 kW
Annual Electricity demand	1576 MWh	1549 MWh	1582 MWh	1535 MWh
Total installed battery capacity	2610 kWh, 3.0 kAh	1740 kWh, 2.0 kAh	2650 kWh, 2.8 kAh	1760 kWh, 1.9 kAh
DoD/Battery life	70 %/12 years	70 %/9 years	70 %/15 years	70 %/12 years
Pack resistance	8.5 mΩ	14.4 mΩ	6.8 mΩ	10.2 mΩ
FCE per day	1.64	2.22	1.75	2.20
Battery replacements	2 times	3 times	2 times	2 times
Light dead weight with batteries	225 t	219 t	230 t	223 t
Fully loaded ship weight	267 t	262 t	273 t	266 t

The WTW life cycle can be divided into well-to-tank (WTT) and tank-to-wake (TTW) stages. WTT refers to energy carrier production and distribution, i.e. valid for charging electricity, HVO, and fossil diesel. The TTW stage refers to the direct impact from the use phase of the ferry, i.e., emissions from the main engine, the auxiliary engine, and the boiler.

3.2. Inventory analysis

The data for the modeling of all six cases and all included processes during different life cycle phases are described in this section.

WTT: The prospective average electricity consumption mix for Sweden between 2025 and 2065 (the ferry operating period) is considered for charging the BEF during the use phase. Prospective electricity mixes are established in steps of 5-year-periods derived from a projection based on the European Commission 2020 reference scenario [33], and combined to establish results for the complete operation period. Details are reported in ESI section 2.7. The inventory data for the electricity infrastructure used in the reference scenario is based on REMIND model [34] assuming the middle-of-the-road development scenario (SSP2) using Nationally Determined Contributions (NDC) for the EU region and are generated using open-source Python library Premise v1.5.8 [35]. This is done to include the time-dependent sectoral transformation of electricity infrastructure (i.e., embodied material and energy in the infrastructure). For the onshore chargers, a substation, power cabinets, a satellite unit, and cables are included in the inventory data. The detailed sub-inventories are described in ESI section 2.6 and are based on two previous studies [36,37].

HVO is a biodiesel, referring to hydrogenated oils and fats from different biological feedstocks. The biological feedstocks modeled for the HVO is based on the present Swedish mix for HVO production, where 76 % comes from animal fats, 12 % from used cooking oil (UCO), and the rest from different vegetable oils [38]. Animal byproducts from slaughterhouses are converted to fats and proteins by rendering, and fats are used to produce HVO by hydrogenation. UCO and vegetable oils can be directly hydrogenated. The hygenization process required for the treatment of the animal byproduct (Category 1 and 2) is not included in the study, as stipulated by the RED directive [39]. The inventory data for all production processes of HVO was gathered from literature [40–42]. The heat required for these production processes was assumed to come from natural gas and modeled with Ecoinvent 3.9 [43]. The electricity for the HVO production processes was assumed to be the same prospective electricity market mix as used for charging the BEF options. The detailed data used in the inventory analysis is given in ESI section 2.2. The production of MGO is assumed as a Swedish market mix based on Ecoinvent 3.9 [43]. For the economic assessment, the costs of electricity, MGO, and HVO are also considered. The electricity cost combines the cost of buying electricity based on average spot price (including taxes) (assumed 46 €/MWh) with grid and power fees (also with taxes), which varies with the power of the onshore charger (assumed 24 €/MWh for 4 MW charger and 14 €/MWh for 0.5 MW charger) [44]. Based on CEIC [45], average MGO and HVO prices are assumed to be 1.2 €/kg and 1.6 €/kg, respectively.

Equipment life cycle: The ship hull and superstructure included for all

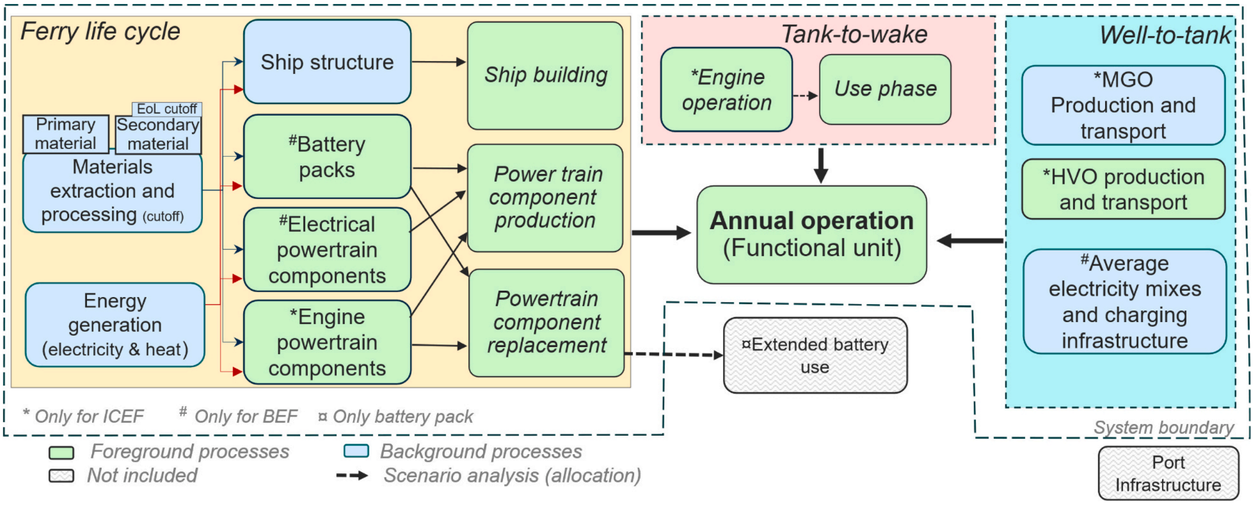

Fig. 2. Life cycle system boundary used in the study: ferry life cycle, tank-to-wake, and well-to-tank. The foreground data combines calculated data with data from previously published works, while the background data is from Ecoinvent v3.9.

studied options are modeled separately and then combined with either the combustion-based powertrain for the ICEF options or the electric powertrain and the batteries used for the BEF options. The total weight of the hull and superstructure is calculated starting from the light dead weight (LDT), followed by removing the weight of the original ICEF powertrain components. The resulting non-machinery ship mass data is combined with generalized ship material composition and production data adopted from Jain, et al. [46]. Corresponding data for the propulsion engines and the auxiliary generators of the ICEF options is based on Kanchiralla, et al. [21]. Table 4 summarizes the components, key parameters, and costs covered in the assessment. Details about the inventory data used for the different ship parts and components are given in ESI Chapter 2.

The electric motors were specifically designed for this study, but generic data for the material inventory and production processes are based on previous LCA studies [47,48]. Inventory data for the six sets of 150 kW inverters (dc-ac) are based on Nordelöf, et al. [49]. The total electricity demand from the grid depends on the power losses in the battery and the efficiencies of the onshore charger and the inverters. For both chemistries, the battery cell format is assumed to be of BEV2 prismatic format. Specifically, the difference in the requirement on C-rate between the two charging strategies is considered based on the model developed by Chordia, et al. [50], which also captures the prismatic cell format. The modeled cells fall in-between being power-optimized and energy-optimized. As a result, sublevel-data, i.e., for the cell components (electrodes, electrolyte, etc.) is based on previous studies [26,28–31,51–53]. The cells are then assembled into modules with liquid glycol cooling for thermal management (also heat transfer plates between cells), and these modules are in turn further combined into battery packs. The battery modules, the thermal management system, the electrical system, and the battery packaging are sized for the case study, using inventory data from three different studies [25,30,54]. The electricity and heat demand for the production of the cells and packs are based on previous studies [53,55]. The details of the data used for the modeling of the battery packs are described in ESI section 2.5.

Inventory data of the heat pump and boiler for inventory analysis is assumed from the previous studies [58,60]. Considering that all parts of the ferry are built in Europe, the extraction and production of materials, heat, and electricity supply mixes that are used as background processes for the production of components are taken from the Ecoinvent database version 3.9 [43], representing European averages, and if European averages are not available, global averages are used.

Replacement: The lifetime of the ferry is estimated to be 40 years, which means that multiple battery replacements are required. For each option, the number of replacements needed depends on the selected SOC interval and total number of cycles as these factors impact battery life. A wide SOC window causes faster degradation to the battery compared to a narrow SOC window [4]. In addition to this, regarding the charge and discharging intensity, there is a differentiation made between calendar effects and cycling effects. *Calendar aging* refers to the degradation process caused by electrochemical and chemical reactions that take place gradually during storage, regardless of battery usage. *Cycle aging* pertains directly to the consequences resulting from the repetitive charging and discharging procedures. For the study, a measure called full cycle equivalent (FCE) is used to calculate the cycle aging degradation as "state of health" for both cell options according to an empirical model presented in Olmos, et al. [4], for a SOC window of 70 %. FCE means that the span of each actual charge-discharge cycle is expressed in proportion to the theoretically full cycle at nominal installed capacity. At the point when this degradation has brought down the available storage capacity to 70 % of its original value, the battery is assumed to be replaced. However, if this does not happen within 15 years of operation, it is assumed that a replacement is needed anyway, due to calendar life degradation [29]. More details on the degradation model are given in ESI section 1.2. It is assumed that the engines of the ICEF options also will require replacements, and this is assumed to be done after

Table 4
Summary of key parameters, cost, and source of inventory data for different components. SFC: Specific fuel consumption; COP: Coefficient of performance; η: Efficiency.

Component	Parameter	Inventory data references	Specific CAPEX	Cost references
Electric motor	Peak η: 97 %	[47, 48][a]	120 €/kW	[56]
Inverter	Peak η: 99 %	[49][a]	100 €/kW	[57]
Main engine	SFC_{max}: 201 g/kWh	[21]	265 €/kW	[56]
Auxiliary generator	SFC_{max}: 230 g/kWh	[21]	350 €/kW	[56]
Heat pump	COP: 3.5 to 4	[58][a]	750 €/kW	[58]
Boiler	η_{Boiler}: 90 %	[58][a]	100 €/kW	[58]
Onshore charger	$\eta_{charger}$: 95 %	[36,37] [a]	300 €/kW	[59]
NMC battery pack	Pack energy density: 159 Wh/kg	[25, 26, 28–31, 50–55][a]	400 €/kWh	ESI 1.3
LFP battery pack	Pack energy density: 128 Wh/kg	[25, 26, 28–31, 50–55][a]	370 €/kWh	ESI 1.3

20 years of operation.

TTW: For ICEFs, the fuel consumption and emissions from combustion depend on the engine load. In the study, a simplified approach for the engine load is used, based on ship speed. During low-speed operation up to 8 knots, and when pushing against the dock while passengers embark and debark, an emission profile corresponding to an engine load of 20 % is considered. For ship speeds above 8 knots, an emission profile for an engine load of 70 % is assumed. In addition, there are emissions from the boiler. However, the boiler operation varies with the season (see calculation details in ESI section 1.1). The emission data used is adapted from Kanchiralla et al. [56,58], and shown in Table 5. The TTW emission for the BEFs is assumed to be zero.

3.3. Impact assessment method

Environmental impacts are assessed for seven midpoint impact categories. The one most in focus is global warming, calculated using characterization factors (CFs) in terms of global warming potential (GWP) for a 100-year perspective according to IPCC AR6 [61]. The six remaining impact categories are particulate matter formation (characterized as PMFP), terrestrial acidification (as TAP), marine eutrophication (as MEP), ozone depletion (as ODP), freshwater ecotoxicity (as FETP), and finally mineral resource depletion, using two different and complementary indicators. The mineral resource depletion impact category is first assessed using the crustal scarcity indicator [62], capturing a long-term perspective on resource scarcity, with CFs (as CSP) reported in [63], and then using the surplus ore indicator to capture a shorter term resource availability perspective [64]. The total surplus ore potential (SOP), as well as the results for all impact categories other than global warming and mineral resource depletion, were calculated using the CFs reported in ReCiPe 2016 v1.03 midpoint (Heirarchist view) [64].

3.4. Economic assessment

The life cycle cost (LCC) model considers all costs that occur at different stages of the product's life cycle and takes the perspective of the ship owner. The calculation formula is shown in Eq. 1, and it can be described as having four contributing parts. The first is the sum of original capital costs, here divided into the costs for powertrain system components (P_C, € for total powertrain system), battery packs for BEFs (B_C, € for total battery pack system), and the rest of the ship (S_B, € per ship). The second part consists of replacement costs, i.e. the sum of added cost from each replacement ($R_{c,x}$) of BEF batteries and ICEF engines. Since the price of battery cells is expected to decrease and the pack design is expected to improve in the future, the cost is assumed to be lowered for each replacement of the batteries. A learning rate of 10 % and 7 % is considered in the assessment for battery cells and the balance of battery system cost, respectively (see details in ESI S1.3). The first and second parts of the formula are then converted to a net present value when the future cost is discounted using a capital recovery factor (*crf*), given in Eq. 2 (where *i* is the interest rate of 10 % and *t* is the ship life of 40 years). The third part of the formula represents variable operation costs, e.g. those related to purchases of electricity or fuel. This is calculated as Electricity/Fuel cost (E_C) combined with annual "fuel consumption" (f_c). Another part of the variable operation cost is the cost of consumables (e.g. Urea for SCR), and it is calculated by multiplying the cost per consumable (C_x) with the annual amount of consumables (N_x). Finally, the fourth part of the formula is fixed operation and maintenance cost (C_O), which is set to 0.43 % of the direct capital cost for the BEF options based on Viswanathan et al. [8] and assumed to be 4 % of the direct capital cost for the ICEF options [56].

$$\mathrm{LCC} = \left((P_C + B_C + S_B) + \sum R_{C,x}\right) \times \mathrm{crf} + \sum E_C \times f_c + \sum C_x \times N_x + C_O \tag{1}$$

$$\mathrm{crf} = \frac{i\,(1+i)^t}{(1+i)^t - 1} \tag{2}$$

In addition to the results for total costs coming out of the LCC model, the study also presents a "carbon abatement cost" with reference to the ICEFMGO option. It is calculated by deducting the total cost of the ICEFMGO option from the results of all other studied options and then, for each, dividing the resulting cost difference with the corresponding GHG savings in terms of global warming potential (as ton CO_2-eq.) for the same studied option and the ICEFMGO option. This means that the presented carbon abatement cost can be defined as the additional cost associated with the abatement of one tonne of CO_2 equivalents for each of the studied options in relation to the ICEFMGO option.

3.5. Alternative scenarios for electricity supply, battery second life, and interest rate

The climate impact results of the BEF options can be expected to be sensitive to the choice of electricity supply mix used for charging. To explore this sensitivity, a sensitivity assessment is performed by varying carbon footprint of the electricity supply from 0 to 800 gCO_2eq/kWh. In addition, a scenario where the batteries being replaced on the ferry go further into an extended life in another application, instead of reaching EoL is also analyzed. An example could be the reuse of cells, modules or complete packs in stationary energy storage. When the battery's diminished state of health renders it unsuitable for transport applications, such storage systems can still make use of it. The introduction of this additional function of the batteries in the study means that the burdens of the original battery production are shared between two different products. To solve the allocation problem either a partitioning of these burdens, or a model system expansion, needs to be done. In this battery second-life scenario, the second-hand cost of the battery pack is assumed to be 15 % of the original pack cost, and an allocation is done based on this monetary value (i.e., economic allocation). This means that 15 % of the impacts associated with battery pack production are allocated to their second life, and consequently their contribution to the ferry life cycle burdens is reduced.

The extended life of battery packs also affects the total cost. Hence, this second life scenario is added in the life cycle cost assessment as well and handled as additional revenue from selling used batteries (15 % of the original capital cost). Lastly, since the BEF options have higher capital costs compared to the ICEF options, they are more sensitive to

Table 5
Inventory data on fuel combustion emissions. Main engine loads for emissions are assumed around 70 % for operational speeds greater than 8 knots and 20 % for other operational modes. The biogenic CO_2 from HVO is not accounted for as contributing to global warming. However, there are CO_2 emissions associated with urea used in the SCR.

Technology used		*High-speed diesel engine*				*Boiler*	
Fuel used		*MGO*		*HVO*		*MGO*	*HVO*
LHV (MJ/kg)		*42.7*	*42.7*	*44*	*44*	*42.7*	*44*
Engine load		*70 %*	*20 %*	*70 %*	*20 %*	*–*	*–*
Specific fuel consumption (g/kWh)		*200.7*	*232.1*	*194.8*	*225.2*	*93.7*	*90.9*
Urea consumption in SCR (g/kWh)		*9*	*9*	*9*	*9*	*–*	*–*
Emissions (g/kWh)	*CO_2*	*648*	*749*	*4*	*4*	*300*	*–*
	CO	*1.1*	*1.1*	*1.1*	*1.1*	*0.20*	*0.20*
	N_2O	*0.034*	*0.034*	*0.034*	*0.034*	*0.02*	*0.02*
	CH_4	*0.01*	*0.01*	*0.01*	*0.01*	*0.002*	*0.002*
	NO_x	*2*	*2*	*2*	*2*	*2.1*	*2.1*
	NMVOC	*0.662*	*0.662*	*0.662*	*0.662*	*0.662*	*0.662*
	PM10	*0.2*	*0.2*	*0.15*	*0.15*	*0.15*	*0.15*
	SO_x	*0.392*	*0.454*	*–*	*–*	*0.187*	*–*
	NH_3	*0.05*	*0.05*	*0.05*	*0.05*	*–*	*–*
	Pre-SCR NO_x	*11.7*	*11.7*	*11.7*	*11.7*	*2.1*	*2.1*

the interest rate (eq. 2). To examine this sensitivity, one additional scenario with a lower interest rate of 5 % is also considered in the economic assessment. The spot price of electricity also varies a lot depending on the supply and demand from all sectors. A sensitivity assessment is performed to understand how the total cost will vary based on average spot electricity price (0–320 €/kWh). It may be noted that the power-related cost and charging infrastructure cost are not changed for the sensitivity analysis.

4. Results

4.1. Climate change

Fig. 3 shows GWP100 results (left side axis) and the energy demand (right side axis) for the annual operation of the ferry options studied. The annual electricity demand (shown with red crosses) for the BEFs are around half of the annual energy demand in fuel for the ICEF options. This is due to the higher efficiency of the electrical system compared to the ICEF setup. When comparing the BEFs regarding charging, the second strategy (options numbered with 2) has 2–3 % lower energy demand compared to the first strategy (options numbered with 1). The reduced energy demand is due to the lower weight of the batteries when more opportunity charging time is offered during shorter dock stops. The LFP chemistry offers the largest weight reduction when combined with the second strategy, due to its lower energy density, resulting in lower total energy demand.

Furthermore, the results show that all BEF options provide more than a 90 % reduction in GWP relative to the ICEFMGO option, whereas the ICEFHVO offers only a 64 % reduction. For the ICEFMGO, the major contributor is the tank-to-wake phase when the fossil fuel is burned, accounting for 80 % of the global warming impact. For the ICEFHVO, the largest contribution comes from the energy-intensive fuel production phase (WTT). It accounts for 90 % of its impact. For BEFs, the major contribution comes from electricity generation (WTT), which accounts for around 65 % of the total impact, followed by battery packs (including initial acquisition and replacements). There are only small differences in GWP among various BEF options. The LFP option under the second charging strategy displays the lowest GWP in comparison to the other BEFs.

A more detailed climate impact contribution analysis is shown for the BEFs in Fig. 4. It also reports the sensitivity to the development of the future electricity supply mix (shown in vertical whiskers), as well as the effect of sending the battery packs to a second-life application (right side bar for each option). With charging strategy 1, the LFP batteries account for 18 % of the total climate impact of BEFLFP1, whereas in strategy 2, the LFP batteries account for 13 %. The NMC batteries are correspondingly responsible for 19 % of the climate impact with strategy 1 and 17 % with strategy 2. Compared to strategy 1, strategy 2 gives 3 % lower climate impact for NMC batteries and 9 % lower for LFP batteries. This is because, with strategy 2, the installed storage capacity is lower compared to strategy 1; however, it may be noted that strategy 2 leads to higher FCE (Table 3). The number of FCE influences the cycle life of both cell chemistries, but the NMC cells to a greater extent. This results in a higher number of battery replacements for the NMC options (three replacements) compared to the LFP options (two replacements). Another observation is that the production of the positive electrodes (grey) clearly makes a larger contribution for the NMC options than the LFP options.

It can be noted that the ship hull and superstructure contribute around 17 % of the GWP of the BEF options. However, the production of powertrain components like electric motors, inverters, and heat pumps does not make a significant contribution to GWP (less than 1 % in total). The impact of the charging infrastructure is about 4 % of the total impact. Fig. 4 also shows the additional scenario analysis, where a share of the battery burdens is allocated to a second life in a stationary application. This gives a GWP impact reduction of 3–4 % in the case of NMC-based BEFs and 2–3 % in the case of LFP-based BEFs. The larger reduction for the NMC batteries can be explained by their higher impact during production.

The WTT electricity supply mix is the largest contributor for all BEF options indicating that the availability of low carbon intensity charging electricity is the most critical factor for climate impact reduction. As the results are based on the relatively low carbon intensity of a Swedish supply mix of 20 g CO_2-eq./kWh (the average of the projection between 2025 and 2065, in the reference scenario). A more carbon-intensive electricity mix would decrease the climate impact reduction potential

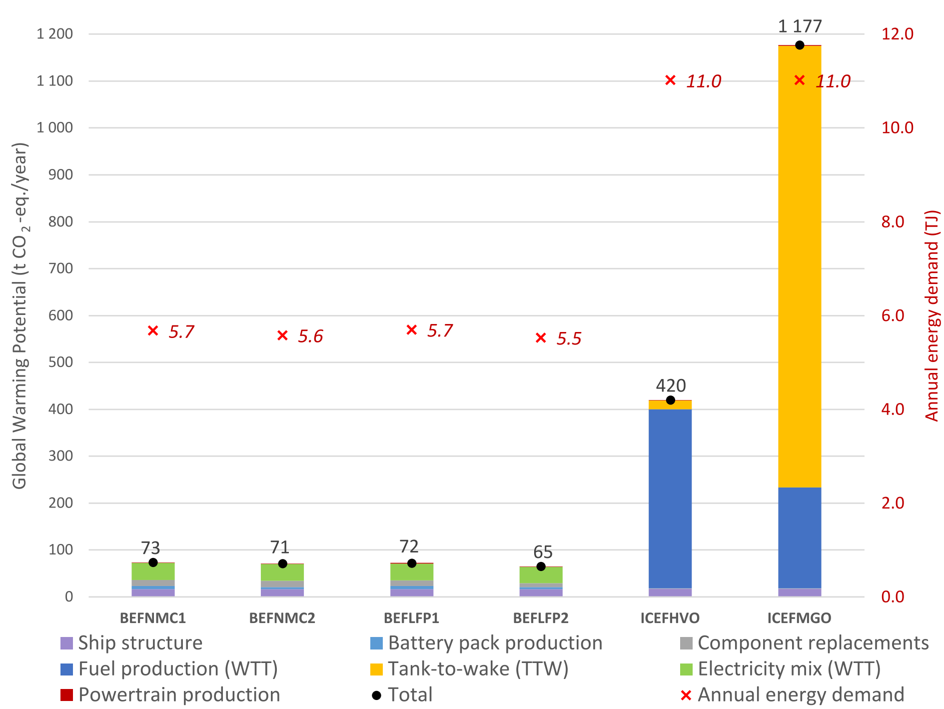

Fig. 3. Cradle-to-grave LCA results on GWP100 and annual energy demand per annual operation of the ferry for the assessed case study.

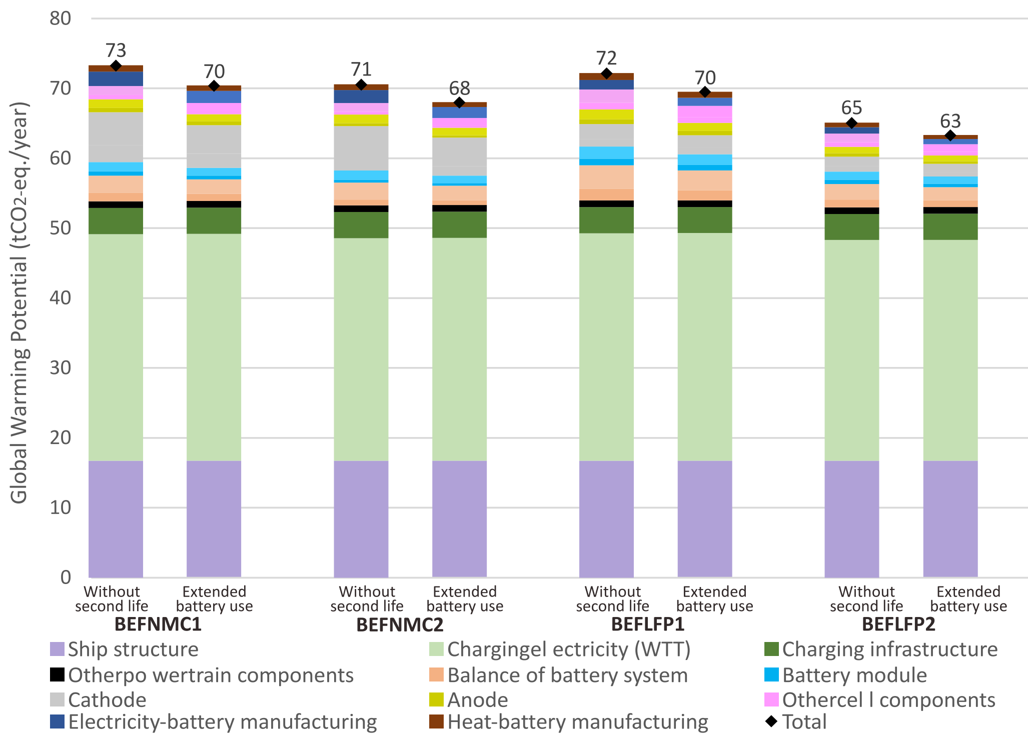

Fig. 4. Breakdown of the GWP for the BEF options including the scenario where a share of the burden from battery production is allocated to a second life application (right side bar for each option) resulting in lower impact from the ferries. Lighter color in each battery component represents impact associated with replacement.

of the BEFs (e.g. the present average carbon intensity of the Swedish supply mix is around 30 g CO_2-eq./kWh and the average EU electricity mix is above 200 g CO_2-eq./kWh). The influence of the carbon intensity of the input electricity on the GWP of the electric ferry is shown in Fig. 5.

4.2. Other environmental impact categories

Fig. 6 shows the four categories where the BEFs are associated with significantly lower environmental impact than ICEFHVO and ICEFMGO options: particulate matter formation (Fig. 6A), terrestrial acidification (Fig. 6B), marine eutrophication (Fig. 6C), and ozone depletion (Fig. 6D). A reduction of around 70 % in particulate matter formation,

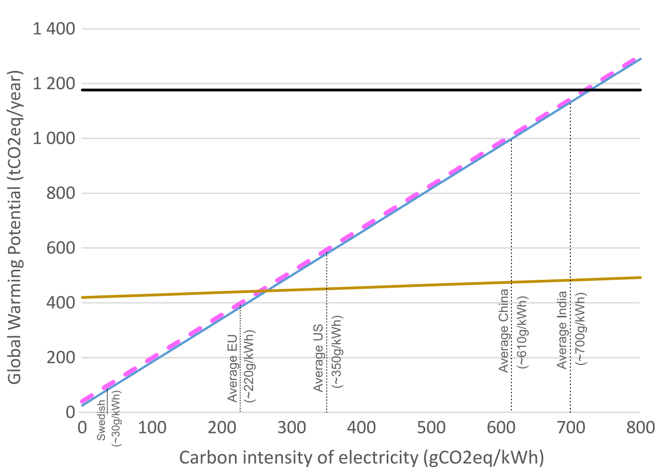

Fig. 5. Sensitivity analysis of thecradle to grave global warming potential (GWP) for the ferry as a function of the carbon intensity of electricity used (0-800gCO2eq/kWh). It may be noted that the various electricity mixes indicated in the figure are the present carbon intensity of the regions reported in IEA [65] and not prospective mixes.

and 70–75 % in acidification potential, is mainly attributed to the absence of NO_X and SO_X exhaust emissions during operation, but also because emissions occur during fuel production. The ICEFHVO option has lower impacts than ICEFMGO, with a decrease of approximately 5 % in acidification potential and 20 % in particulate matter formation, mainly due to lower sulfur oxide emissions. BEFs also exhibit significantly lower marine eutrophication potential (around 65 % lower) and ozone depletion potential (85–90 % lower) compared to the ICEFMGO. However, using HVO in the ICEF is associated with a large increase in marine eutrophication (9 times higher) and ozone depletion (3 times). As can be noted from Fig. 6, these impacts are mainly linked to fuel production and the major contribution can be linked to the use of vegetable oils from cultivated feedstock for HVO production. If 100 % of the feedstock for the HVO used would be waste-based (many common feedstock routes for HVO are), the impacts would be lower. In comparing NMC to LFP batteries, it can be seen that LFP offers lower environmental impact than NMC for all impact categories, especially for particulate matter and acidification potential (both around 20 % lower). Similar to GWP, these differences in impacts are associated with differences in battery production, and especially the impact of the active material in the positive electrodes.

Fig. 7 shows impact categories that are linked to resource use and extraction. These are generally more burdensome for the BEF options in comparison to ICEFMGO or ICEFHVO options. Ecotoxicity (Fig. 7C) is an impact category where the BEF cases are associated with a significantly higher impact (6 times) than that of the ICEFMGO. This is mainly due to toxic emissions from the extraction and processing of metals like copper and zinc used in the electricity infrastructure, powertrain components, and battery packs. Other important contributors are materials used in battery cell production such as lithium carbonate for both cell types and nickel for the NMC cells. The ICEFHVO option has a higher ecotoxicity impact compared to the ICEFMGO which is mainly linked to copper and zinc used in the electricity and fuel production infrastructure.

The crustal scarcity indicator and surplus ore indicator (as SOP) results for the BEF options are dominated by the battery pack constituents and metals coupled to electricity generation. In the case of SOP, the

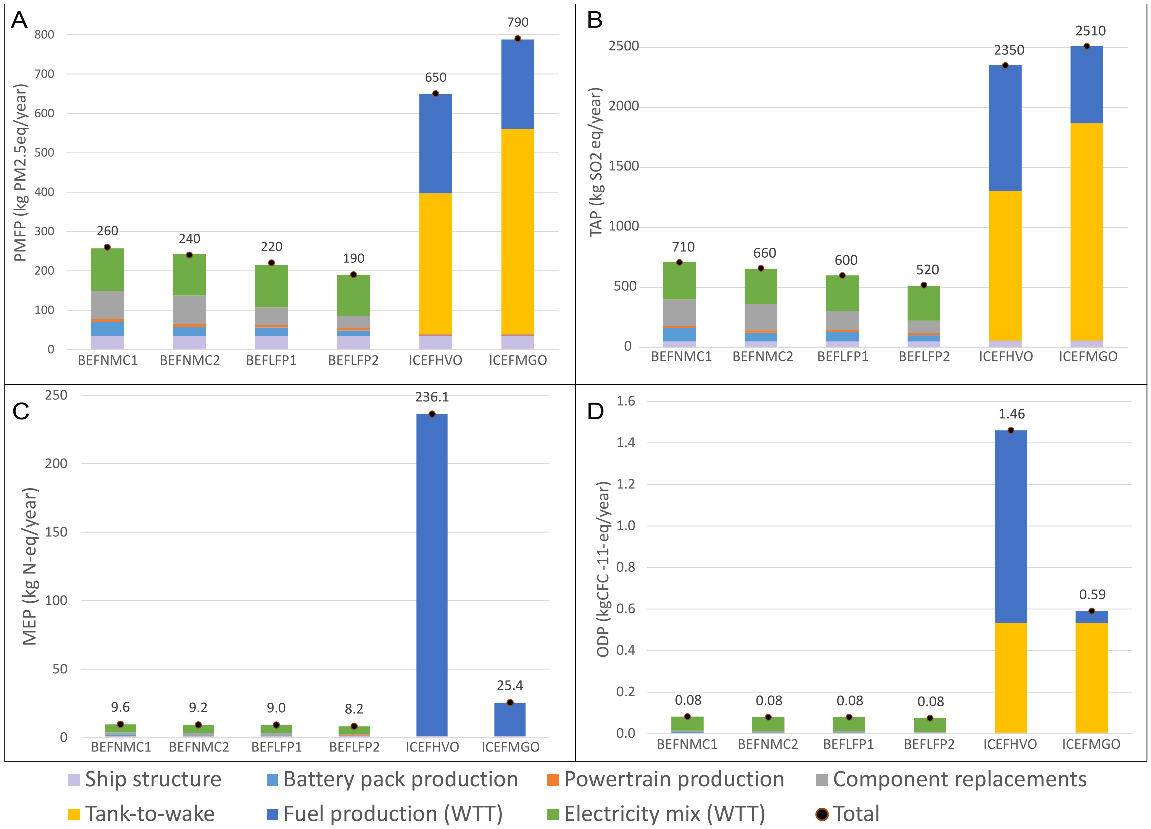

Fig. 6. LCA results for the impact categories that have a lower impact for BEFs than HVOICE and MGOICE. PMFP: Particulate matter formation potential, TAP: Terrestrial acidification potential, MEP: Marine eutrophication potential, ODP: Ozone depletion potential.

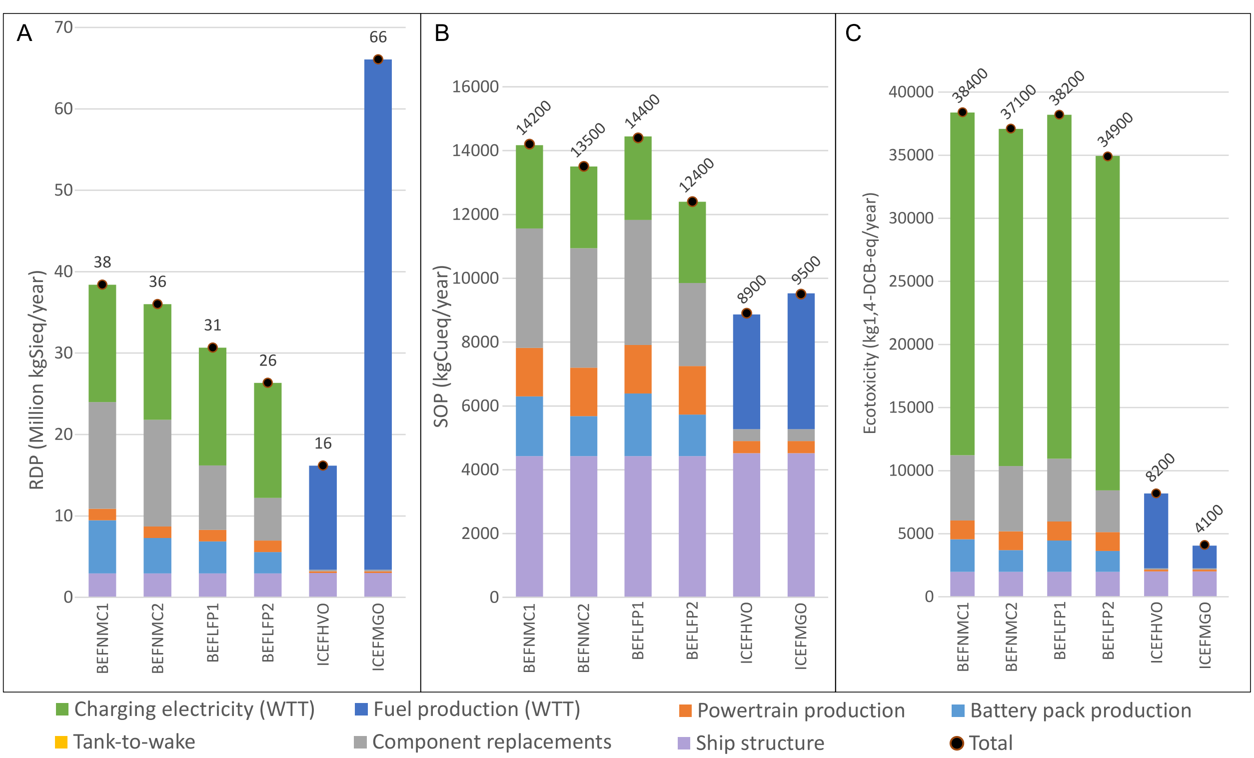

Fig. 7. Impact assessment results for two indicators covering mineral resource depletion – the crustal scarcity indicator in RDP providing a potential for long-term scarcity and the surplus ore indicator (SOP) providing a short perspective on resource availability – and freshwater ecotoxicity. Common for all these impact categories is that the BEF options generally have a higher impact than ICEFHVO or ICEFMGO options, except for the CSP of the ICEFMGO.

largest contribution comes from lithium extraction for battery cell production, followed by the extraction of rare-earth elements (REEs), used in wind farms for electricity generation and in the electric motors. For NMC battery packs, the cobalt and nickel extraction also contribute notably to the SOP results. In addition to REEs, copper contributes significantly when considering the impacts of the electricity infrastructures that supply the charging electricity. When considering CSP results for the BEF options, the largest contributors are uranium, extracted to become fuel in nuclear power plants, and REEs for use in wind turbines, i.e. both coupled to electricity generation for charging. However, the production of battery packs also significantly contributes to the CSP results, primarily due to the extraction of lithium and copper (for both battery types), and nickel and cobalt (for NMC batteries). It can also be noted that the crustal scarcity indicator in resource depletion potential covers fossil resources, whereas they are not covered by the surplus ore indicator. This explains the very high CSP value for the ICEFMGO option. For both the CSP and SOP results, the ICEFHVO has the lowest impact.

4.3. Economic assessment

Fig. 8 presents the economic assessment results for the BEF and ICEF options. It can be noted that the BEFs have higher total life cycle costs compared to the ICEFMGO for the base case interest rate, and also for the second life application scenario. The highest cost share apart from the hull and superstructure cost is associated with the battery packs. It can be noted that for the first charging strategy, where the installed battery capacity is higher, the total BEF cost is 10 % higher than the ICEFMGO cost, and on par with the total cost for the ICEFHVO. All BEF options have carbon abatement costs lower than ICEFHVO. However, with charging strategy 2, all BEF options have lower total cost, and notably lower carbon abatement costs, than the ICEFHVO. This indicates that adapting the operation profile to accommodate more charging, not only reduces the need for installed energy storage capacity and the linked environmental impact but also the total life cycle cost. The additional scenario where a part of the economic cost (15 %) is assigned to the second life of the battery (shown in red) provides an example of how the BEF with the LFP battery pack can be cost-competitive with the MGO-powered ICEF. This indicates further that aiming to optimize the DoD and SOC window to enhance battery life (and enable second-life use) is important also from the cost perspective.

Since the LFP battery cost is lower than the NMC battery cost in both strategies, the BEFLFP options also have a lower total cost. This is reflected in the carbon abatement cost as well, where the LFP options have a carbon abatement cost of less than 100 €/tCO_2eq. Another important contribution to the cost of the BEFs is the annual electricity cost. However, it is still lower than the annual cost of fuel for the ICEF options. This means that the BEFs have lower operation costs compared to ICEFs, and this is because of the high TTW efficiencies of the BEFs.

Fig. 8 also presents the scenario with a lower interest rate of 5 %. Here it can be noted that with such an interest rate on the capital investments, all BEF options have lower total costs than the ICEFs, and as this comes together with lower overall GHG emissions, the benefit is double, and the abatement cost turns to negative values. This significant reduction in the total cost is due to the higher investment cost of battery packs for BEFs in relation to ICEF options (Fig. 8). Overall, this indicates that policies that can support investments, e.g. reduced lending rates or subsidies, could be an effective way to support the electrification of ferries.

Electricity and charging infrastructure account for 20 % and 5 % (total 25 %) of the total cost of the BEFs, respectively. Furthermore, almost half of the electricity cost is directly linked to grid charges based on the power drawn from the grid rather than direct energy use. This means that optimizing the charging power can also reduce the total cost without affecting the operation. However, it should be noted that the electricity spot price in Sweden, is one of the lowest in the world [66]. A sensitivity analysis of total cost for the first charging scenario as a function of electricity spot price is shown in Fig. 9.

5. Discussion

The economic performance and environmental impact of different BEF variants and diesel-based ICEFs are evaluated over their production and operation life cycle stages. Irrespective of the battery chemistry and charging strategy employed, BEFs can achieve significantly lower climate impact and reduce several other environmental impacts, including acidification, marine eutrophication, particulate matter formation, and ozone depletion, in comparison to ferries powered by different variants of fossil diesel such as MGO or biodiesel in the form of HVO. These reductions in environmental impacts are mainly associated with emission-free operation which compensates for the emissions caused during other life cycle stages of the ferry. The electricity (for charging), battery packs (original acquisition and replacements), and ship hull and superstructure are the three broader hotspots when considering the contribution to total impacts. However, a tradeoff exists for BEFs regarding resource utilization and freshwater ecotoxicity, primarily due to metals such as copper, zinc, cobalt, nickel, lithium, and REEs present foremost either in battery packs or in the infrastructure

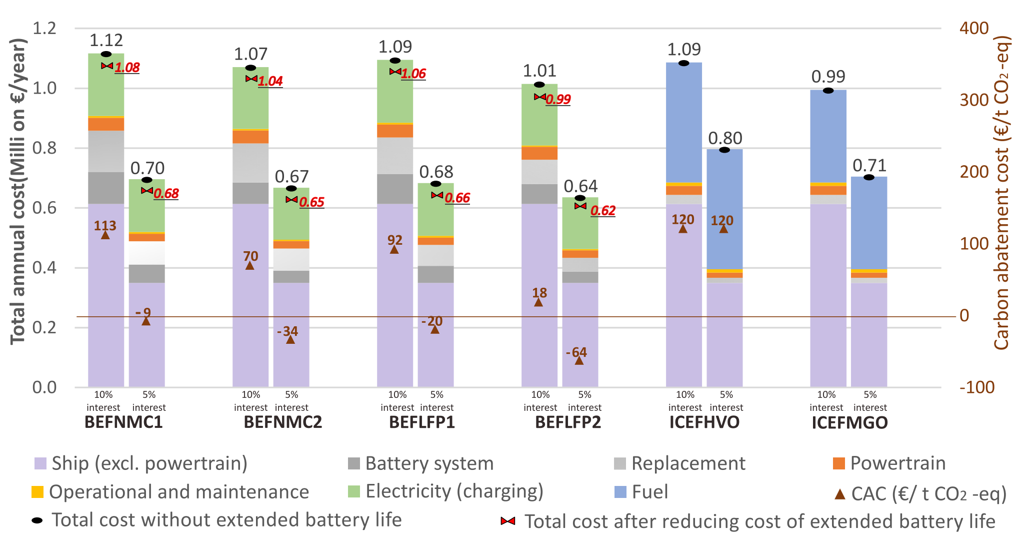

Fig. 8. LCC results for the six cases assessed for the functional unit annual operation of the ferry.

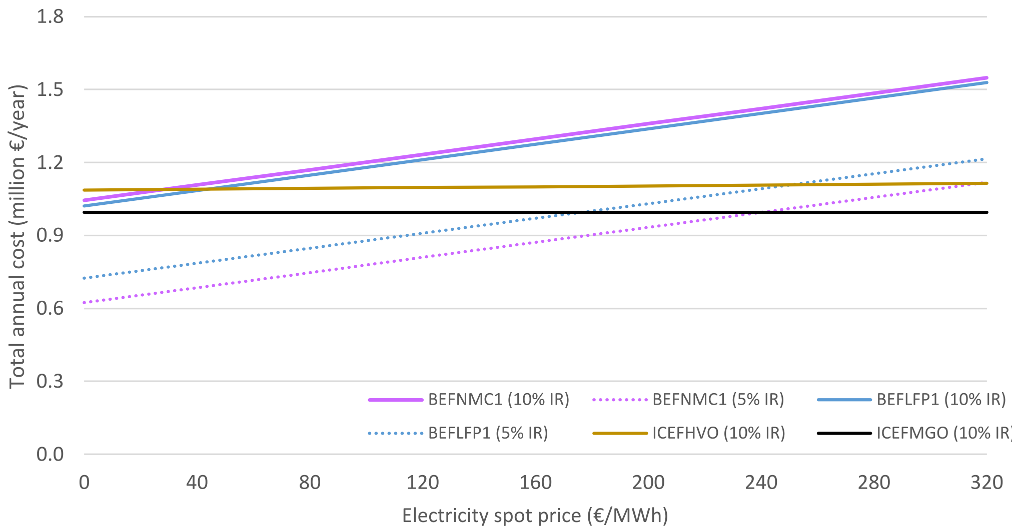

Fig. 9. Sensitivity analysis on total cost as function of average spot electricity price on total annual cost including all life cycle stages. IR-Interest rate.

and plants for electricity generation and distribution. The ecotoxicity impact and resource use can be improved with better recycling and stricter environmental regulation on primary material extraction [67].

It is challenging to directly compare the results of this study with other studies due to differences in scope and assumptions, e.g. the electricity mixes supplied during charging. The GWP reduction potential reported in other studies ranges from as low as 15 % [19,22] up to as high as 90 % [20,21] when compared to different fossil diesel. This variation in the results is directly attributable to the choice of electricity mix. Charging with a carbon-intensive electricity mix will offset a large share of the climate impact reduction potential that can be achieved using BEFs. The sensitivity analysis conducted in this study indicates that since the ferry will operate for a long time, it is important that electricity with a low carbon intensity is accessible for charging. It also shows that the future operation of the ferry may be affected by changes in the future availability of cleaner electricity; future BEF operation may be further improved if more GHG-free electricity is made available. These environmental impact results and conclusions align well with other studies of public transportation, e.g. city buses, as shown by Nordelöf, et al. [67]. Other aspects that impact the environmental performance are the type of ship and its operational pattern which will determine the size of the battery in relation to the amount of electricity charged. This study also highlights that the installed battery size can be considerably reduced if the time available for opportunity charging is increased on energy demanding routes. Such a schedule adaption could reduce both total cost and environmental impacts by increased utilization of the installed batteries.

Among the BEFs, the BEFLFP has lower life cycle environmental impacts and lower total cost than the BEFNMC. The higher impact coupled with the use of NMC batteries compared to LFP, can be explained by higher emissions in the NMC active material production and its supply chain. Similar results can be observed in other studies [30,51]. However, there are studies that indicate that LFP batteries cause higher GHG emissions compared to NMC batteries [29]. This discrepancy arises from the variations between the supply chains considered [26], uncertainty around the energy densities for both cell types and choice of processes and technologies applied in production [52]. The future development of cell and pack energy densities is important both regarding environmental and economic cost performance, as such improvements reduce the material and energy demand of the battery production for each kWh of capacity installed [53]. In addition, higher energy densities can reduce the weight of the ferry, in turn reducing the energy demand for propulsion.

The charging strategy is critical in determining the required usable battery capacity. The comparison of the two strategies included in this study shows that better planning for opportunity charging at different docks during the daily route can reduce both total environmental impact and total cost by reducing the required battery capacity. This study has not considered varying the SOC interval or the charging power. Such investigations could provide further useful input when tuning all parameters to minimize the total cost of ownership. The second charging strategy shows that optimizing the design for the specific application can make BEFs competitive even without supporting policies for the case study vessel. Nonetheless, this is dependent upon the electricity prices for charging, and the study applies the regional electricity price in Sweden, which is lower than in most geographical areas of the world. Reduced interest rates or subsidies for installation costs will also increase the cost-competitiveness of battery-electric ferries. Alternatively, it is shown that a carbon tax of about 100 €/t CO_2-eq. may be enough. The SOC interval plays a significant role in determining the installed capacity and also the life of the battery, this study has not evaluated different SOC intervals. It is recommended to include this in future studies as a small SOC interval results in a longer battery life and reduces the number of replacements. On the other hand, a small SOC interval would lead to increased installed capacity, resulting in a heavier BEF and a higher energy demand for propulsion. Moreover, spot electricity prices vary over time of the day and seasons, often following a peak-valley structure. It is recommended that the economic impact of this is included in future work. Another limitation of the study is that the current HVO production mix is considered to be valid for all years. Environmental implications of future HVO production from different feedstocks is another relevant topic for in future work.

6. Conclusion

The study gives a detailed assessment of battery electric ferries considering a combination of factors such as the electricity sources used for charging, the specific battery technology chosen, battery lifetime, the supply chain of battery production, and the strategies employed for charging. The result shows that electrification can significantly reduce climate impact, acidification, marine eutrophication, particulate matter formation, and ozone depletion of public transport ferries. However, there are environmental tradeoffs like resource use and ecotoxicity. The burden is shifted to the production phase and associated with primary metal extraction from the earth's crust for batteries and infrastructure for electricity. The exact numerical results should be interpreted with caution, as it will vary with the carbon intensity of the electricity mix. Among the battery types compared, LFP batteries are preferable over

NMC622 batteries in terms of life cycle environmental impact and cost competitiveness. However, this preference may alter depending on future developments. The main impacts associated with the NMC battery type come from the cathode material production, relying on nickel and cobalt. Implementing appropriate charging strategies that improve opportunity charging can enhance the competitiveness of battery electric ferries, but it necessitates modifications to the operational pattern. Accessibility to reasonably priced electricity for charging is crucial for the competitiveness against fossil-powered ferries, and policy support for investments is recommended.

CRediT authorship contribution statement

Fayas Malik Kanchiralla: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Emma Grunditz:** Writing – review & editing, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Anders Nordelöf:** Writing – review & editing, Validation, Methodology, Data curation, Conceptualization. **Selma Brynolf:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Evelina Wikner:** Writing – review & editing, Validation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2025.126274.

Data availability

The data used is attached in supplementary information.

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