Life Cycle Analysis and Cost Assessment of a Battery Powered Ferry

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ABSTRACT

Battery-powered ships constitute a solution to the pathway to zero-emission shipping. This article studies comparatively and assesses the performance of battery-powered vessels implementing the Life Cycle Analysis (LCA) and Life Cycle Cost Assessment (LCCA). A case study of a battery-powered fast catamaran ferry is employed and comparatively assessed against the respective conventional ferry revealing the advantages and drawbacks of these two alternative solutions. LCA and LCCA take into account the different ship life phases and activities to develop a life cycle emission inventory and estimate the corresponding costs. The results demonstrate that the battery-powered system exhibits life cycle GHGs reduced about 30% when grid mix electricity in 2019 is utilised and life cycle costs reduced by 15% in comparison with a conventional power system.

KEYWORDS

Battery-powered ferry, Life cycle analysis, Environmental-economic assessment, Electric vehicles, shipping decarbonisation

ABBREVIATIONS

CF , Carbon conversion factor

CML , Centrum voor Milieuwetenschappen

CO_2 , Carbon dioxide

EB , Electricity required for battery packs

ECA , Emission control area

ER , Energy requirement of engine

EU , European Union

FC , Fuel oil consumption of the engine

GHG , Greenhouse gases

GWP , Global warming potential

GWP100a , Global warming potential in 100 years period

LCA , Life cycle analysis

LCCA , Life cycle cost assessment

LCI , Life cycle inventory

LCIA , Life cycle impact analysis

LIBs , Lithium-ion batteries

LHV , Lower heating value

MARPOL , The international convention for the prevention of pollution from ships

MDO , Marine diesel oil

M_{CO2} , the CO_2 emissions amount (in kg) generated from fuel combustion

NOx , Nitrogen oxides emissions

PV , Photovoltaic

SFOC , Specific fuel oil consumption

SOx , Sulphur oxides emissions

1. INTRODUCTION

In recent years, the decarbonisation of our society has become a global emergency linked to the witnessed climate change. The CO_2 emissions are the largest contributor to the global warming effect and a contributing factor to acidification. Although there are many gases with higher global warming potential, CO_2 has been identified as the most significant GHG due to the substantial quantities released from the burning of fossil fuels. According to the data collected by the World Bank, the annual global CO_2 emissions were more than 36 billion tonnes, whereas the other substantial released GHGs were methane and NO_2 with about 8 billion and 3 billion tonnes respectively in 2012 (Sommer et al., 2019).

International shipping is one of the most efficient transportation means with the largest quantity of goods transportation and the least air pollution contribution. According to IMO's Fourth GHG Study in 2020, international shipping accounted for 2.2% of the global total anthropogenic CO_2 emissions (IMO, 2020). However, to limit the global temperature rise according to the goal of the Paris Agreement and the vision of the United Nations (Committee on Climate Change, 2019), GHG emissions from the marine sector should be properly addressed. Urgent actions are also required to meet IMO's new targets, using 2008 as a reference: 40% CO_2 reductions by 2030 and 70% CO_2 reduction by 2050, and at least 50% reduction on the total annual GHG emissions by 2050 (IMO, 2018). One of the most promising near-term solutions to meet this timetable is a battery-powered ship, benefitting from the parallel developments in the automotive industry which provides a solid base for the development of marine solutions (Divya and Østergaard, 2009; Vicenzutti et al., 2015).

Battery-powered ships are the solution to zero-emissions shipping. In most cases of the conventional and hybrid-electric ship power plants, the electric power is still generated by the main engines (as power take-off) or diesel generator sets, which burn fossil fuels to supply mechanical power and electricity. One of the proposed solutions to replace them and limit the use of fossil fuels onboard the ship is the battery-powered ship concept, which intends to use electricity generated from renewable sources onshore. It is now actively applied and investigated for high-speed passenger ferries, as it is not feasible for large ocean-going vessels yet. However, for speeds over 20 knots, no such ferry has been constructed. On the other hand, a battery system has many advantages eliminating the hazardous emissions in route, offering also a more stable system that requires less maintenance, and achieving a higher scrapping price as more parts can be reused, e.g., battery cells, containers etc.

Hybrid systems, combining engines and batteries using a mixture of electricity, and sometimes other renewable resources, have been investigated for many years (Dedes, 2013; Jeong et al., 2018; Ling-Chin and Roskilly, 2016). Sanfelix et al. (2016) evaluated both the environmental and economic performance of the lithium-ion batteries (LIBs) and concluded that the manufacturing stage has the highest environmental footprint while using grid electricity (Sanfélix et al., 2016). (Dai et al., 2019) investigated the application of Li-ion batteries on electric vehicles indicating the main environmental impact contributor of the batteries are from production and compared the environmental impacts of grid electricity and electricity from renewable sources on the production phase. Another interesting research carried out by Zhao and You presented and compared the environmental impacts of four different types of cathode materials of Li-ion batteries and also concluded the most significant contributor to life cycle GHG emission is the cell production phase (Zhao and You, 2019). (Matheys et al., 2009) has assessed five different battery technologies for electric vehicles to identify the most environmentally friendly one with the least overall environmental impact. Similarly, the research carried out at the University of Oldenburg (Hiremath et al., 2015; Mitavachan, 2014) investigated four different stationary battery technologies on their cumulative energy demand and global warming potential. However, the results showed the impact from the operational phase of batteries dominates the life cycle impact which contradicts the results from other researchers.

In the meantime, the applications of batteries on marine vessels are still under development by investigating, analysing and comparing different propulsion configurations (EMSA, 2020). Kluiters et al. have tested the application of sodium/nickel chloride batteries for ships back in 1999. Due to the limitations of the available battery technology, the sodium/nickel chloride battery was found to be superior only to the sodium/sulphur battery (Kluiters et al., 1999). However, in the last decade, many researchers have turned their focus on the ship application of batteries. Lan et al. (Lan et al., 2015) have carried out a study to investigate the optimal size of a hybrid ship power system combining solar energy, a diesel generator and a battery system. The goal was to minimise the initial investment and the operating costs and the carbon dioxide emissions release of the ship while considering the solar irradiations and the temperature along the voyage. Misyris et al. (Misyris et al., 2017) also developed an estimation algorithm to illustrate the battery state during the ship operation.

To identify and evaluate the environmental performance of marine propulsion systems, LCA is widely adopted which could cover cradle to grave stages in the battery life cycle. LCA has been adopted to assess the environmental sustainability of a Thai Island's diesel/PV/wind hybrid microgrid (C. Smith et al., 2015). There are applications of LCA in automotive vehicle production such as the material selection, and forming process from scrapped materials (Delogu et al., 2016; Raugei et al., 2015; Raugei et al., 2014). Bolbot et al. also expanded the LCA to include cost, environmental and safety assessment to optimize a cruise ship power plant with different fuel combinations (Bolbot et al., 2020). (Blanco-Davis and Zhou, 2014) Wang et al. have investigated the performances of solar-assisted power systems comparing a traditional power system on a short route ferry operated in Istanbul (Wang et al., 2019).

Furthermore, many applications of LCA refer to battery system evaluations. It is common in the automobile industry research to apply LCA to assess and compare the environmental impacts of such systems (Dunn et al., 2016). The E-Ferry project (Abrahamsen, 2020) has indicated that applying the batteries on their ferry, replacing diesel engines and fuel oils, can bring down the operator's cost by 24%−36% and reduce by 2000 tonnes the CO_2 emissions over a 30-year operation.

However, the research on the application of the LCA on marine battery-powered vessels is still in its infancy. Therefore, it is important to determine the advantages of a battery-powered vessel comparing to a conventional one with a holistic environmental impact perspective.

This study aims to perform an LCA for a battery-powered ferry for comparing the performances of conventional marine engines and innovative battery power plants to quantify the benefits of replacing marine diesel engines and generator sets with a battery system and electric motors. A sensitivity analysis is carried out to determine the impact of the electricity mix and engine energy efficiencies and demonstrate the advantages of the battery-powered system. Several parameters including emissions and cost are employed to estimate the influence of the battery technology on the fleet operation. This study contributes to the field literature by examining the life cycle view of battery and engine performance comparison and continues to provide an LCA approach to support the marine industry designers to assess and select the optimal alternative between different options.

The remaining part of this study is structured as follows. The description of the employed methodology is provided in Section 2. In Section 3, the details of the case ship study are presented including the required input for the implementation, the considered design scenarios based on different marine propulsion systems and the analysis of the energy consumption of the vessel. The equivalent battery-powered version is analysed to determine the battery size, capacity and electric power demand. Section 4 provides the following three LCA steps: 1) Adaption of LCA to the case ship study; 2) Marine sector customised LCA method development and an LCA model is developed in GaBi; 3) Results of the analysis are provided and compared including emissions inventory and key performance indicators/metrics. In Sections 5 and 6, the impacts of battery-powered plants and consideration on operational cost and fleet management are presented. The main findings of this study are summarised in Section 7.

2. METHODOLOGY

2.1. Overview

The methodology followed for accomplishing the aim of this study includes the following four steps according to ISO (ISO, 2006):

1) Determine the system boundaries

It includes the description and boundaries of the system under consideration, input data required and the formulae associated with the data.

2) LCA implementation

This study employs LCA to quantify and normalise the life cycle emissions of the target ferry, mainly focusing on the greenhouse gases (global warming potential). A customised model is used for the case study ship to fit the purpose of comparing the battery-powered and conventional marine power plants.

3) Systematic comparison process

An approach to extending and convert the emissions to life cycle costs is followed and employed to determine an indicator for comparison.

4) Recommendations

The recommendations from the analysis are provided for the case study ship and subsequently extended to the whole fleet.

2.2. System Analysis

The system analysis is the first step and defined and shown in Figure 1, which will focus on the performance of the ship including the emissions released and the cost associated with them. The stages and interactions inside the analysed system are presented in Figure 2 that shows the determination of indicators such as emission generation and energy demand.

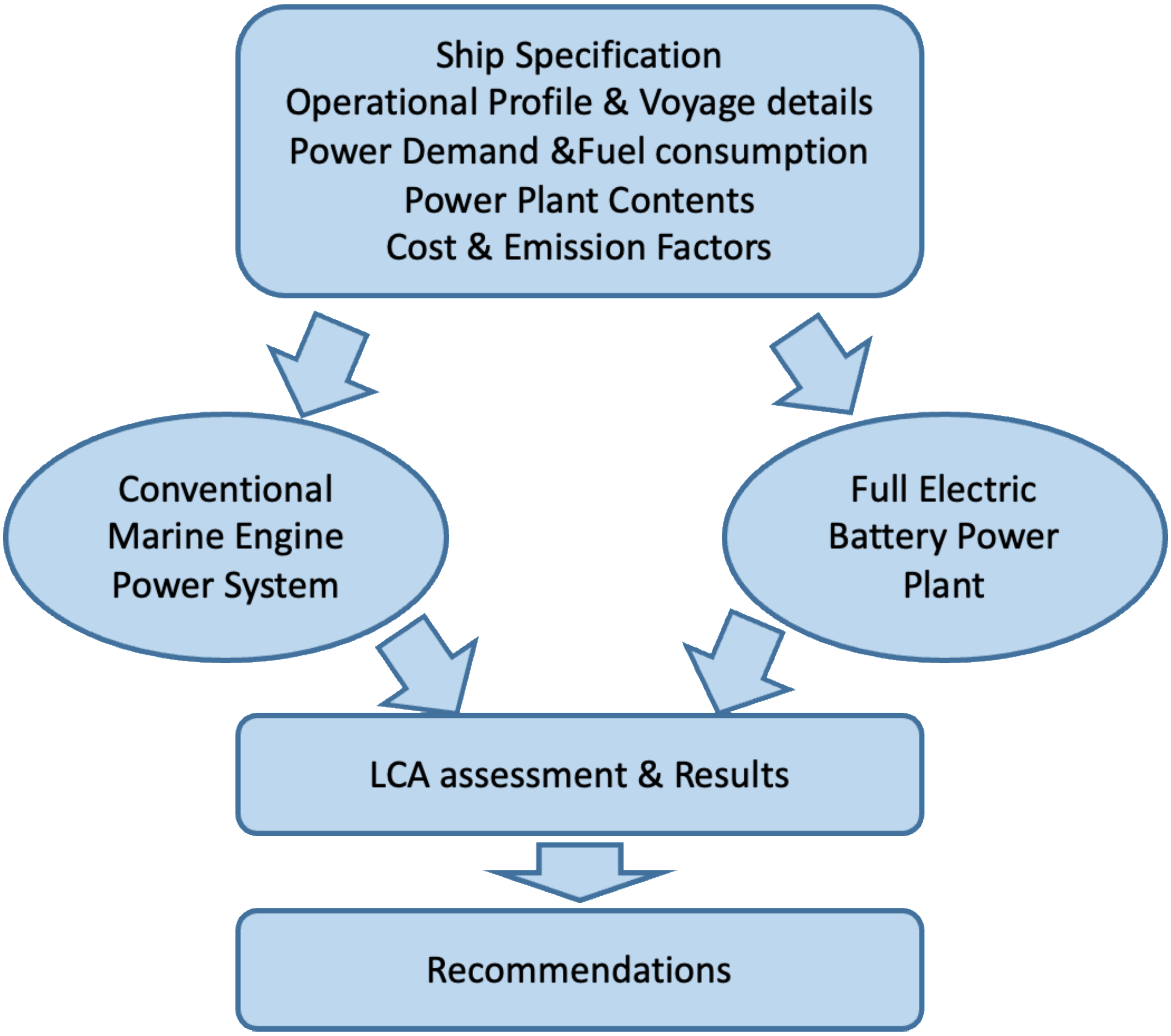


Figure 1 Methodology overview

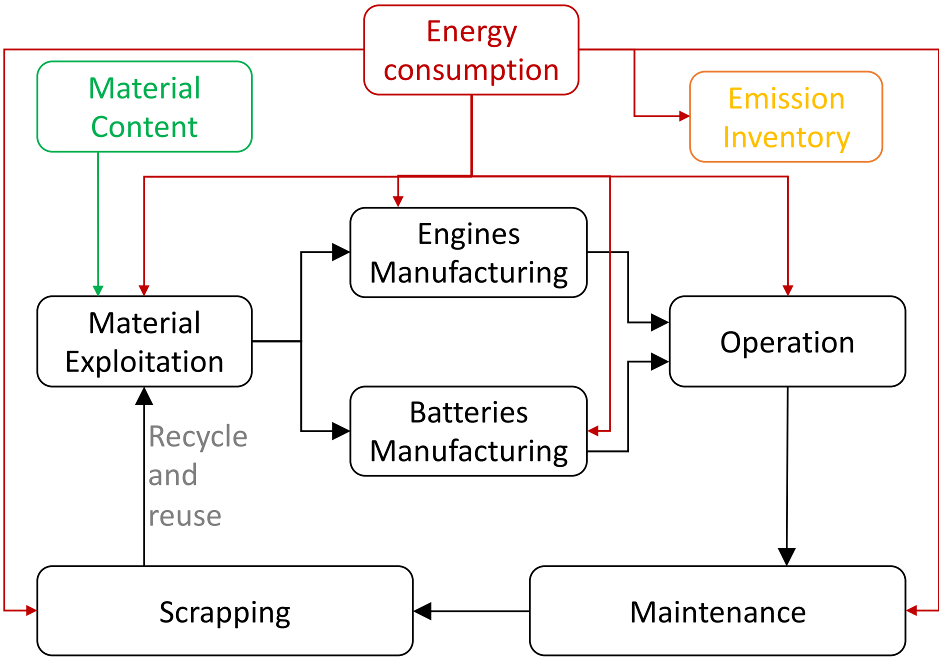


Figure 2 LCA stages and interactions

The carbon emissions and the batteries electrical energy are estimated by using the following equations.

1) Carbon emissions' estimation (Smith et al., 2015)

$$M_{CO2} = FC \times CF \quad (1)$$

Where, M_{CO2} is the CO_2 emissions amount (in kg) generated from fuel combustion; FC denotes the engine(s) fuel oil consumption (in kg); and CF is the carbon conversion factor (for marine diesel oil, the CF = 3.206 kg CO_2/kg MDO (Smith et al., 2015)).

2) Estimation of electricity required from battery packs

$$E_B = E_R/r \quad (2)$$

$$E_R = FC \times LHV \quad (3)$$

Where, E_B is the electricity required for battery packs (in kWh); E_R is the energy that must be covered from the engines (in kWh); r is the overall efficiency of using electricity including charging from shore power and onboard utilisation; FC is the engine(s) fuel oil consumption (in kg); LHV is the fuel lower heating value (in kWh/kg)

3) The energy efficiency of conventional engines is estimated by the following equation (Chakraborty, 2019):

$$\eta = ER/(LHV \times FC \times t) \quad (4)$$

Where, η is the energy efficiency of the engines; ER is the energy requirement of the engines, kWh; t is the engine operational time (in h); FC is the engine fuel oil consumption (in kg); LHV is the fuel lower heating value (in kWh/kg).

3. LCA ON CASE SHIP

This study investigates a short route inland waterways fast ferry operating in Thames River, London, UK. The battery-powered version of this ferry's power plant is analysed and compared to its conventional alternative to eliminate the consumption of any fossil fuel onboard and avoid any tailpipe emissions. In this section, the data collection will be presented which will be used to support the development of the LCA model and assessment. The specification of the case study vessel is shown in Table 1 and the route of the vessel is presented in Figure 3 using route planning application (plotaroute, 2021). The route of the ferry is along the Thames River, servicing between 13 piers and the service duration is about 18 hours per day. This study will identify the performance of the battery power system (includes battery energy storage stations, management system, switchboard, converters etc.) and determine its advantages compared to conventional propulsion systems (marine engines).

Table 1 Case study ship specifications

Main particulars			
Hull type	Catamaran	Speed (knot)	28
Length overall (metre)	35	Block coefficient	0.58
Length btw. Perpendiculars/ Length of Water Line (metre)	32.54	Midship coefficient	0.85
Breadth (metre)	8	Prismatic coefficient	0.69
Depth (metre)	2.35	Waterplane coefficient	0.84
Draught (metre)	1	Geometric displacement (tonne)	75
Operation days (day)	320	Daily operation hours(hour)	18
Propulsion type	Waterjet	Froude Number	0.81

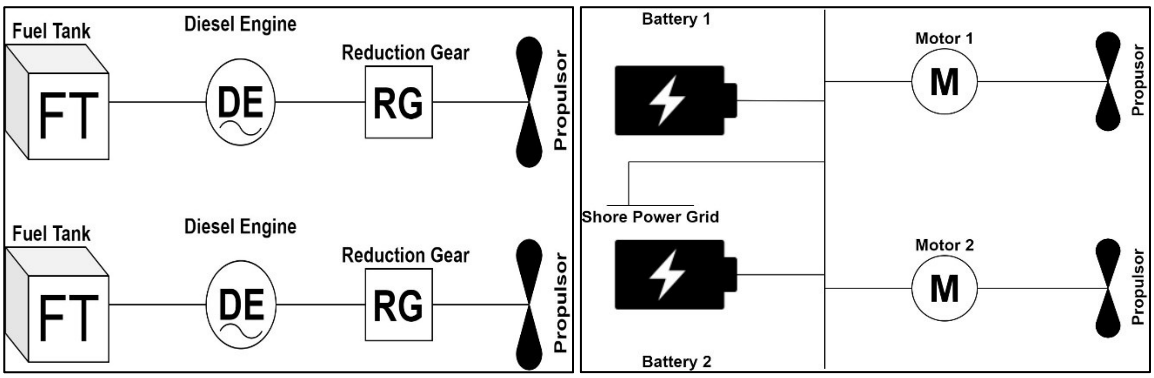
Figure 3 Operating route of the case study ferry (Thames Clippers, 2020)

3.1. Case Scenarios

Two alternative propulsion system scenarios will be considered: 1) application of marine diesel engines (conventional system); 2) application of the battery-powered electric system.

3.1.1. Case 1- Use marine diesel engines

This is the baseline scenario where a conventional propulsion system utilising two diesel engines, one in each demi-hull. The ferry will be operated 18 hours per day and 320 days per year for a life span of 30 years. Each round trip will last 3.6 hours and the idling time at destinations will be about 0.35 hours (21 minutes). The engine power system is presented in Figure 4 (A)



(a) (b)

Figure 4 Layout of power plants: (a) conventional; and (b) battery powered

3.1.2. Case 2- Use battery powered system

In this scenario, the engines and their fuel will be replaced by a battery-powered system capable of propelling the vessel at the same speed. Electric energy storage will replace the thermal energy of the marine diesel oil so the emissions from ferry operation will be eliminated but the upstream emissions from the electricity generation must be considered. The battery power system is shown in Figure 4(b).

3.2. Preliminary Analysis

Based on the data provided by the ferry operator, the fuel consumption of a basis ferry operated in the same route was recorded and analysed (Figure 5). The fuel oil consumed by both the port and starboard engines during the operation is shown in this figure. The data has been normalised to protect their confidential character. Based on the recorded fuel consumption provided by the ship operator, the energy requirement for a round trip is estimated at 650kWh with an overall energy efficiency of around 38%.

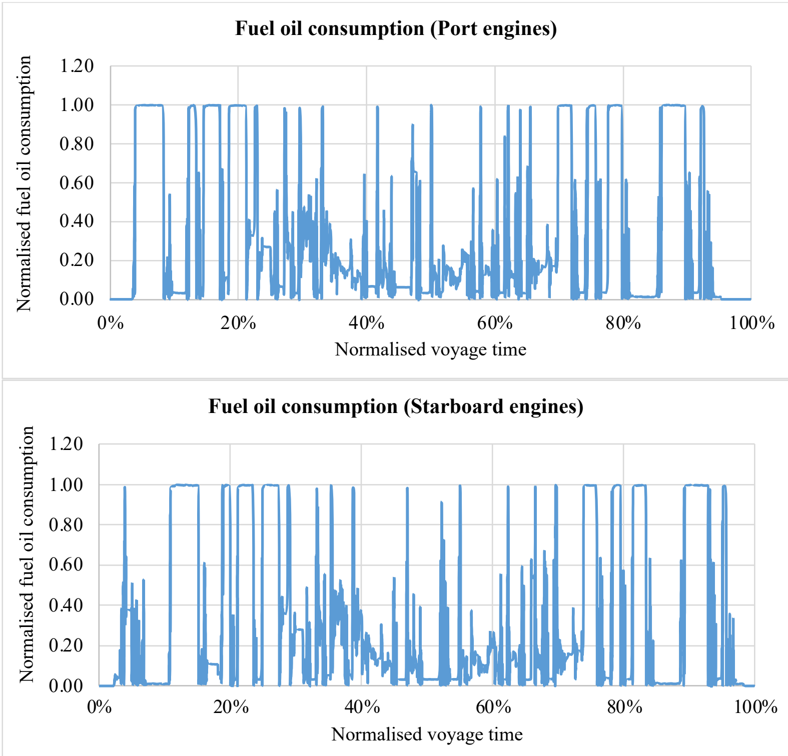


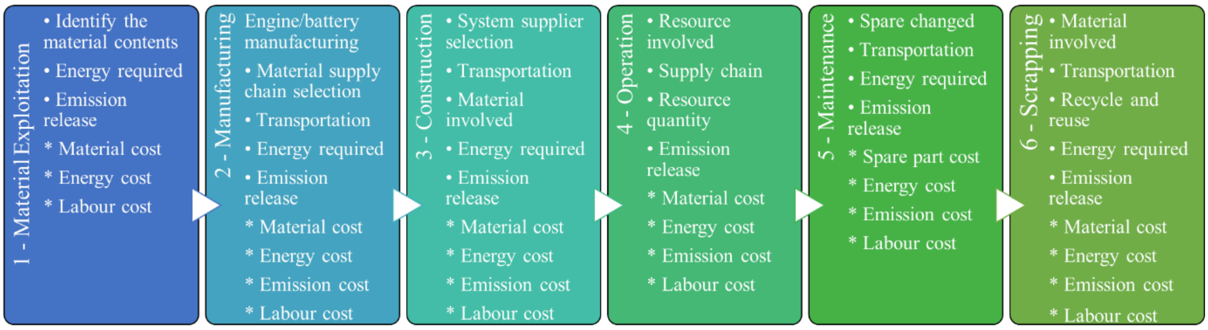
Figure 5 Normalised port and starboard engines fuel oil consumptions

3.3. LCA Study

This section presents the LCA analysis on the short route inland waterways catamaran high-speed ferry under the two different scenarios. The approach from Section 3.3 is applied.

3.3.1. Goal and Scope

The goal of this LCA study is to determine the environmental impacts of the two different power systems on marine vessels (ferry in this case). The target audience is marine sectors including, shipyard, ship operator, researchers and policymakers. The benefits of applying the battery-powered system will be derived from its comparison with the diesel engine from the perspective of environmental impacts. Usually, there are five phases of the onboard power system (Figure 2): material exploitation, system manufacturing, utilisation phase, maintenance periods and end-of-life (decommissioning). Under the various phases, the associated material, energy and emissions will be under consideration as shown in Figure 6 (for further study, cash flow will be considered). To retrieve the material, energy and emission flow, the main activities under these phases should be identified along with the associated data.



*These are collected for life cycle cost assessment.

Figure 6 Flow chart of life cycle phases and data collection master checklist

The method can be simplified without significant loss of its accuracy by a series of assumptions made based on engineers' judgement and industry's practices:

A) The assumption is made that all the dimensions of the vessel (hull form and displacement) remain unchanged when replacing engines and fuel tanks with battery packs and electric motors. Since the differences between the two cases are only the propulsion/power systems, the comparison and evaluation focus on these systems;
B) The functional unit is the annual energy consumption per ship operational year; for engine power system it is linked to the fuel consumption and in a battery power system it is related to electricity used; all over the ship life span, all the phased and activities can be connected or converted by considering this functional unit;
C) Due to the growing attention on the global warming effect, this study will investigate the impacts of power systems on the global warming potential of the ferry; in this study, CML 2001, an impact assessment method, is selected to characterise the emissions in the life cycle inventory (CML, 2016);
D) The diesel fuel oil and energy consumption are determined using data provided by the shipowner and ship operator which has shown and determined in Section 3.2;

E) The electricity in this baseline study is sourced by a mix of different energy sources for which includes fossil fuel consumptions, such as hard coal, natural gas, fuel oil and so on (Department for Business, 2020; GaBi, 2018; Raugei et al., 2020);

F) Emissions generated from engines running and electricity required by the battery packs are estimated using equations in Section 2.2;

G) The scrapping phase is simulated based on the energy required and emissions generated according to Jeong et al., 2018;

H) The GaBi software is applied to build the LCA model for the case study vessel (Figure 7 & Figure 8): Blue lines represent the material and system flow; Green lines show the electricity flow; the heavy fuel oil required by transportation is shown using black lines; the fossil fuel and lubricating oil used in operational phase are indicated by red colour which is zero in the figure because it illustrates the battery-powered ferry which has battery packs replacing the engines; light blue is used to show the natural gas required from scrapping process.

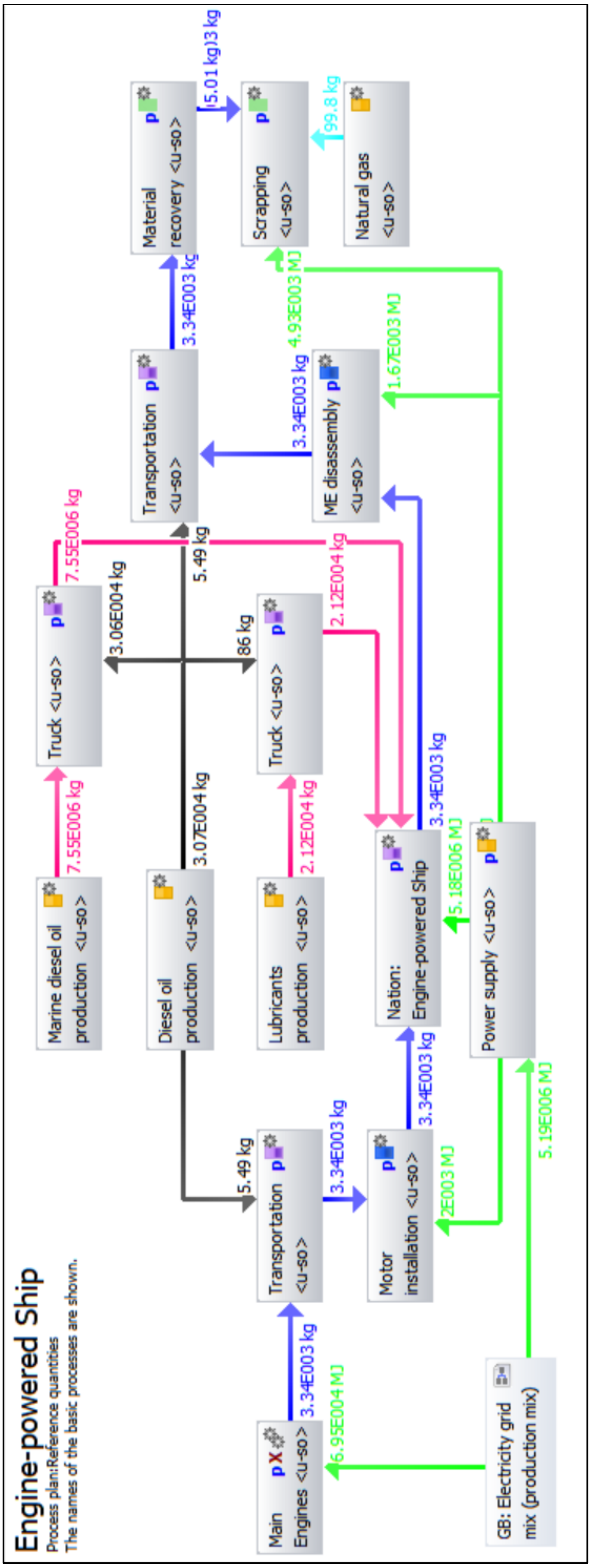


Figure 7 Life cycle modelling of the case ship with marine diesel engines

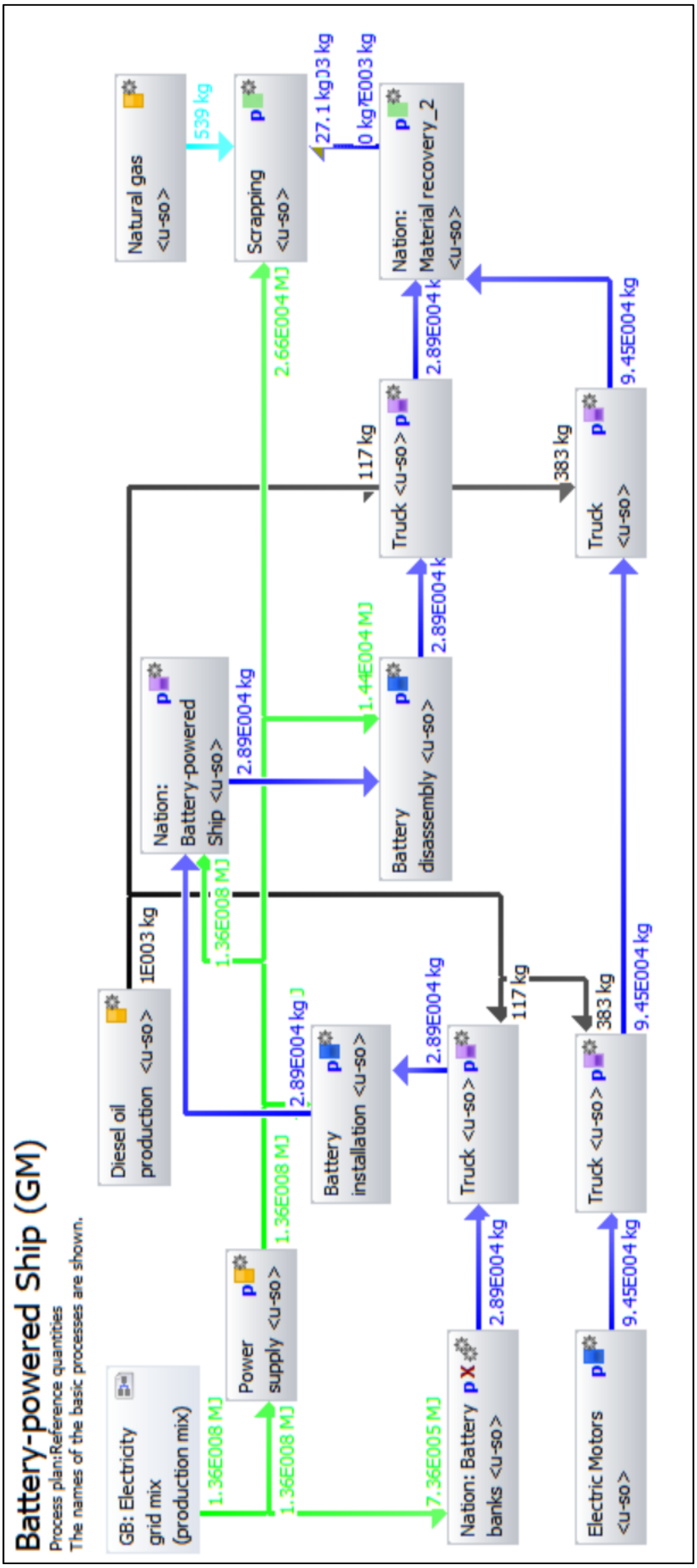


Figure 8 Life cycle modelling of the case ship with the battery-power system

3.3.2. Life Cycle Inventory Assessment

The materials of the engine are listed in engine manufacturer datasheets in Table 2 (SCANIA, 2016). The battery under investigation is Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) — NMC type and the materials components of the battery are shown in Table 3 (Daniel, 2008). The raw material exploitations, production and manufacturing for engines are studied according to aluminium and iron ore production processes for the automotive industry investigated by Salonitis et al., 2019 shown in Table 4. The same energy consumption will be applied for the battery case and the extra energy required for battery cell manufacturing is estimated using data provided by Thomitzek et al., 2019. The latter indicates that the energy required is about 0.58 Wh/Wh battery capacity.

The weights and costs of the battery packs are determined according to the battery supplier (Corvus, 2021) and Mossali et al., 2020. The energy density and the cost for Li-ion batteries are taken 5.68 kg/kWh and 120–241 £/kWh respectively (Corvus, 2021). The cost of the marine diesel engine is estimated according to Mossali et al., 2020.

With the software GaBi and its database, the following emissions inventory is developed: which is customised to the emissions of interest in Table 5. The foreground and background databases are presented in Table 6 & Table 7.

Table 2 Material content of typical marine diesel engine

Engine material	Weight ratio (%)
Steel	40.0
Cast iron	46.0
Aluminium [Al]	8.0
Copper [Cu] and Zinc [Zn]	0.2
Lead [Pb]	0.1

Table 3 Material content of lithium-ion batteries (LIB)

Material/Component	Weight ratio (%)
Cathode	41.0

Anode	16.4
Binder	4.7
Current collector (Cu)	4.4
Carbon	1.4
Current collector (Al)	1.8
Electrolyte	18
Separator	1.8
Tabs, end plates, terminal assemblies	1.9
Container	8.5

Table 4 Energy required for raw material exploitation, production and manufacturing (MJ/kg)

Processes	Iron	Aluminium
Iron ore mining	0.6	-
Limestone mining	0.2	-
Coke manufacturing	2	-
Iron ore agglomeration	1.6	-
Smelting	13	-
Bauxite mining	-	0.8
Alumina refining	-	25.4
Anode production	-	1.4
Electrolysis	-	54.1
Anode consumptions	-	14
Ingot casting	-	1.8
Melting	3.9	6.5
Holding	0.2	
Making	1.13	3.5
Fettling	0.12	0.6
Machining	1.6	0.051
Ancillary process	1.95	-
Liner casting	-	0.6
Total	26.3	108.75

Table 5 Emissions inventory for the power plant Life Cycle of 30 years

Emission	Conventional (kg)	Battery-powered (kg)
Ammonia	6.22	126
Carbon dioxide	2.79×10^{7}	1.90×10^{7}
Methane	3.61×10^{4}	5.04×10^{4}
Nitrogen oxides	6.29×10^{5}	3.94×10^{4}
Nitrogen monoxide	0.329	57.6
Sulphur dioxide	1.33×10^{4}	3.09×10^{4}
Sulphur trioxide	0.0097	0.252

Table 6 Foreground input data collected

Item	Value	Unit	Source
Annual Operation Days	320	days	Operator
CH_4 Factor	0.0003	kg/fuel-kg	(IMO, 2020)
CO Factor	0.0074	kg/fuel-kg	(IMO, 2020)
CO_2 Factor	3.114	kg/fuel-kg	(IMO, 2020)
Daily operation hours	18	hours/day	Operator
Life Span	30	years	Operator
Batteries Mass	3750	kg	(Corvus, 2021)
Main Engines Mass	3340	kg	(SCANIA, 2016)
NOx Factor	0.087	g/kWh	(IMO, 2020)
Particular matters	1.2	g/kWh	(IMO, 2020)
Sea Margin	15	%	(SCANIA, 2016)
SFOC	219.92	g/kWh	(SCANIA, 2016)
SLOC	0.65	g/kWh	(SCANIA, 2016)
SO_2 Factor	0.02	kg/fuel-kg	(IMO, 2020)
Sulphur Content	1	%	(IMO, 2020)

Table 7 Background input data collected from GaBi database

Electricity mix in the UK in 2019			
Hard coal	36.41		%
Natural gas	26.62		%
Nuclear	19.66		%
Wind	7.92		%
Grid losses	7.63		%
Rest	1.76		%
Carbon intensity	0.537		kg CO_2-eq per kWh
Transportation per 100 km			
Payload	17.3		t
Sulphur content	10		ppm
Carbon dioxide in fuel	5		%
Motorway	70		%
Rural	23		%
Urban	7		%
Utilisation rate	85		%
Emissions from fuel oil production			
	Diesel	Lubricating oil	kg
Ammonia [sea water]	0.000197	3.33×10^{-7}	kg
Ammonia [air]	2.23×10^{-16}	1.42×10^{-10}	kg
Ammonia [fresh water]	0.000197	3.33×10^{-7}	kg

Carbon dioxide [air]	0.372	0.940	kg
Carbon monoxide [air]	5.64×10^{-4}	1.13×10^{-3}	kg
Chemical oxygen demand (COD) [sea water]	0.000186	0.000301	kg
Chemical oxygen demand (COD) [fresh water]	3.30×10^{-5}	3.40×10^{-5}	kg
Ethane [air]	0.000215	0.000242	kg
Ethene (ethylene) [air]	2.97×10^{-10}	2.02×10^{-10}	kg
Hydrogen chloride [air]	2.63×10^{-6}	7.08×10^{-6}	kg
Methane [air]	4.22×10-3	4.86×10-3	kg
Nitrogen oxides [air]	7.80×10^{-7}	5.51×10^{-8}	kg
Phosphate [fresh water]	6.53×10^{-5}	8.12×10^{-6}	kg
Sulphur dioxide [air]	1.58×10^{-3}	3.8×10^{-3}	kg
Toluene (methyl benzene) [air]	8.99×10^{-8}	1.42×10^{-7}	kg

3.3.3. GWP focused Life Cycle Impact Assessment Results

This section will present the GWP results of characterising the GHG emissions in the LCI by applying the CML characterisation model (CML, 2016). The results are determined not only considering the emission mentioned in the inventory in this study but also many other insignificant and low quantity emissions included in the GaBi database. The comparison of results between ferry with marine diesel engines and the battery-powered electric system is presented in Table 8. From the table, it is observed that with the battery-powered electric propulsion system on the ferry instead of diesel engines, the global warming potential is reduced by around 30% across the ship's whole life span.

Table 8 Global warming potential impact of the investigated plants for a life cycle of 30 years

Global warming (GWP100a) - CML-IA baseline		Unit
Ferry with a conventional system	2.88×10^{7}	kg CO_2-eq.
Ferry with battery system	2.03×10^{7}	

3.4. Sensitivity Analysis and Discussion

3.4.1. Parameters selection for sensitivity analysis

Since the battery-powered system could lead to a 30% reduction of GHG emissions in the case ship study, it is still not enough to achieve the challenging target of reducing 40% of carbon dioxide (CO_2) by 2030 or reducing 50% of the GHG emission release by 2050. The main source of the GHG emissions during the life span of the battery-powered ferry comes from the electricity generation process which, in this analysis, uses supply from grid mix in the UK. In Section 3.4.2., the impacts of using different energy sources for electricity generation will be investigated.

A weight and size comparative assessment was carried out in Section 3.4.3 to further consider the impact of replacing diesel engines with batteries from the perspective of weight and size.

3.4.2. Sources of electricity

Four energy sources of electricity are under consideration: grid mix in 2019 and 2050 (UK Government, 2020), hydropower and wind power. The results are compared with previous baseline studies (engines using marine diesel oil and battery using grid mix electricity in 2019). The comparison results are shown in Table 9 and the scenario with marine diesel oil presents the case ship with engines. From the results, the observation is that around 99% of GHG emissions can be avoided when applying electricity from renewable sources, comparing to use marine diesel engines or grid mix electricity on the ferry.

Table 9 Global warming potential for different sources of electricity for a life cycle 30 years

Global warming (GWP100a) - CML-IA baseline		Unit	Reduction Rate
Marine diesel oil for conventional power plant	2.9×10^7		Baseline
Electricity (mix in 2019) for battery power plant	2.0×10^7		29.5%
Electricity (mix in 2050) for battery power plant	4.0×10^6	kg CO_2-eq.	86.2%
Electricity (hydro) for battery power plant	3.1×10^5		98.9%
Electricity (wind) for battery power plant	2.6×10^5		99.1%

3.4.3. **Weight and size comparative assessment**

This study has discussed the impacts of applying a battery power system from the perspective of emission reduction and cost-saving. It is attractive to indicate the impact on the overall design from the perspective of system weight and size. In this section, a further comparison of the diesel engine power and battery power system will be carried out on their weights and volumes. According to the battery factsheet provided by the manufacturer, the dimensions, weight and energy capacity are derived and presented in Table 10. Regarding the diesel engine power system, a basis ship of the case study ferry was selected with the same overall length (LOA) and length between perpendiculars (LBP), passenger capacity and operational profiles, breadth, draft and service speed. The details of its engines have been presented in Table 10 for comparison reasons. From the table, the dimensions of the battery modules and diesel engines are provided, and the volume taken on board the ferry can be directly determined. The case study catamaran ferry is equipped with two sets of power systems, one on each demihull. It is estimated that the two sets of batteries occupy 33 m^3 which is a much larger space than the one taken by two diesel engines (5.72 m^3). The fuel carried on the diesel-powered ship is 2.6 tonnes or 2.92 m^3 in volume. From the weight perspective, the engine weighs 1.67 tonnes according to the manufacturer (SCANIA, 2012a). The weight and energy capacity of one battery module is about 375 kg and 66 kWh. The battery energy required to support one round trip is 650 kWh and the battery will be charged while idling at terminals with a charging power of 2000 kW (from manufacturer). Considering the state of charge (SOC) of the battery and charging, it should be controlled between 90% and 20% (Wartsila, 2020) and can be recharged by 1200 kWh per day (36 minutes charging). The derived capacity of the whole battery system is 5080 kWh, comprising 77 single battery modules. The total weight of the battery packs and electric motors (GRELECTRIC, 2020) amounts to 36.46 tonnes. Comparing this with the total weight of 5.9 tonnes of the conventional propulsion system underlines the challenges the designer of a battery-driven vessel is facing as the battery power system will occupy more space and increase the displacement of the vessel.

Table 10 Comparison between batteries and diesel engines

Power system	Battery	Engine	Unit
Height	5800	1214	mm
Width	2450	1251	mm
Length	2110	1551	mm
Total volumes	31.7 (33 m^3 for batteries + 2.7 m^3 for motors)	8.6 (5.7 m^3 for engines + 2.9 m^3 for fuel)	m^3
Total energy	5080	-	kWh
Total power	-	625×2	kW
Total weight	37.5 (28.9 t for batteries + 7.6 t for motors)	5.9 (3.3 t for engines + 2.6 t for fuel)	t

4. LIFE CYCLE COST ASSESSMENT

The cost assessment is a part of the LCA which considers the costs and benefits from the battery-powered ship all through its life span compared to the traditional version. The cost assessment is in parallel with the LCA which can share the same scope and model. In a cost assessment, the cash flow will be tracked including the investment, operational expenditures and cost related to maintenance and scrapping. The purpose of the cost analysis is not only to determine the cost associated with the target but also to compare the difference between different alternatives/options. As the focus of this study is to evaluate the cost impact of applying a battery system on short-route ferries, the investment and scrapping will be considered based on the energy and transportation fuel consumption from the GaBi model. A cost of 286 £/kW was used for engine cost estimation (Wu and Bucknall, 2016). The maintenance phase is considered by using the strategy proposed in Jeong et al., 2018. The battery life span is provided by the manufacturer which is about 10 years so there will be two battery system changes in the 30 years life span. The operational phase is the most important phase to be considered, which will present the advantages of applying a batteries system comparing to a conventional system. During the operation of the conventional propulsion system, the highest cost comes from the consumption of fuel oil which can be determined based on the equation from the previous section with the MDO fuel price (313 £/tonne) and lubricating oil price (401 £/tonne) derived from online (Bunkerworld, 2020; U.S. Bureau of Labor Statistics, 2020). For battery-powered vessels, the operational costs are due to the electricity consumption and the electricity price for a large industrial company is derived as 9.58 pence per kWh in the UK (Department for Business Energy & Industrial Strategy, 2019). In this study, the size of energy consumption, the ship operator, is a small company. The prices of electricity have been assumed to be the same for three different sources which need further discussion to determine the impacts of electricity prices on the ferry's operational cost. The cost estimations for the ferry's operation considers both the operational cost and cost associate with the environment. A carbon credit is selected as 18 £/tonne (World Bank, 2020) to estimate the environmental cost which can be determined by the production of carbon credit price and quantity of equivalent carbon dioxide emission. The costs of charging station construction are not under consideration.

From Table 11, it is observed that the operational cost of the battery system (electricity consumption) is 26% higher than the conventional system due to low fuel price but the total life cycle cost is lower by 15%. It is financially beneficial to replace the conventional propulsion system although the current fuel price remains low. Therefore, from the view of life cycle economy, a battery-powered system can reduce both GHG emissions and life cycle costs.

Table 11 Life cycle cost analysis of ferry for the investigated power systems

System	**Energy source**	**Construction (GBP)**	**Operation (GBP)**	**Maintenance (GBP)**	**Scrapping (GBP)**	**Carbon credit cost (GBP)**	**Total cost (GBP)**

Conventional system		4.10×10^5	3.21×10^6	5.69×10^6	1,182.65	5.18×10^5	9.31×10^6
Battery-powered system	Grid mix electricity	1.30×10^6	4.05×10^6	2.59×10^6	2,240.28	3.65×10^5	7.94×10^6
	Electricity from hydro	1.30×10^6	4.05×10^6	2.59×10^6	2,240.28	5.58×10^3	7.94×10^6
	Electricity from wind	1.30×10^6	4.05×10^6	2.59×10^6	2,240.28	4.75×10^3	7.94×10^6

5. FLEET CONSIDERATION

The application of a battery power plant on one short route ferry could reduce global warming potential so it will be interesting to consider the whole fleet from ferry operator to have battery power system adopted on all the ferries. Table 12 presents the details of a ferry fleet operated in Thames River. The quantities of saved fuel, carbon emission and reduction potential when applying battery power plant for the fleet can be determined (Table 13) with the following assumptions:

1) All the ferries in the fleet have an operational life span of 30 years;
2) 2 battery replacements will be carried out;
3) Each ferry will be operated 18 hours per day;
4) It is assumed the engines of these ferries will be operated under their optimal loads;
5) The fuel-carbon conversion factor is set to be 3.206 kg/kg fuel,
6) The electric supply comes from the Electricity grid mix in 2050 so the reduction rate is 86.2% comparing to the engine power system.

The results of this fleet consideration use the forecast and roadmap of the UK electricity mix to be decarbonised in 2050. It shows with the grid mix electricity in 2050, the whole fleet will reduce over 2.25 million tonnes of CO_2-eq.

Table 12 Fleet information (Thames Clippers, 2020)

Ship	No	Length (m)	Breadth (m)	Width (m)	Design speed (knot)	Power (kW)	Engine type
Ferry #1	1	38	8.78	-	<25	662 x 2	DI16 077M
Ferry #2	6	38	9.6	9.3	28	1120 x 2	MTU 10V 2000 M93
Ferry #3	2	35	8.3	8.3	30	625 x 2	DI16 072M
Ferry #4	2	35	8.3	8.3	30	625 x 2	DI16 072M
Ferry #5	2	32	8.13	7.8	25	596.92 x2	Caterpillar 3406E
Ferry #6	3	25	-	5.7	25	625 x 2	DI16 072M

Table 13 Carbon emission reduction of the fleet for 30 years operation.

Engine Type	No of vessels	Engine Power (kW)	Daily Operating hours	SFOC (g/kWh)	Daily Fuel consumption (t)	Overall Carbon Emissions (t)	Overall GWP Reduction (t)	Reference
DI16 077M	1	1324	18	215	3.84	1.22×10^{5}	1.08×10^{5}	(SCANIA, 2012b)
MTU 10V 2000 M93	6	2240	18	240	43.55	1.38×10^{6}	1.22×10^{6}	(MTU, 2006)
DI16 072M	7	1250	18	219	25.87	8.21×10^{5}	7.24×10^{5}	(SCANIA, 2012a)
Caterpillar 3406E	2	1194	18	220	7.09	2.25×10^{5}	1.99×10^{5}	(Caterpillar, 2020)
Total	16				80.35	2.55×10^{6}	2.25×10^{6}	

6. CONCLUSION

This study investigated the impact of applying a battery power system on an inland high-speed catamaran passenger ferry from the perspective of environmental footprint with emphasis on the global warming contributions. The LCA approach was applied to consider essential life processes and activities in the vessels' life span, covering the exploitation of raw materials, production of systems, construction, operational and scrapping phases. An LCA model was established in GaBi software to take all these phases and activities into account and an LCI inventory was established to cover all the emissions from the targeted emission categories. Eventually, after characterisation of the LCI results, a comparative study was carried out to compare the impact of different power system alternatives. It was derived that comparing to the conventional power system (marine engines consuming fossil fuels), the ferry with battery system could achieve about 30% of life cycle GHG emissions reduction when grid mix electricity (with 0.537 kg CO_2-eq./kWh) supply is selected. However, due to the challenging emission reduction target from IMO, two more considerations of electricity from two other power generation sources were made: hydro and wind power. The reduction rates could reach up to 99% compared to the conventional ferry.

Hence through developing an LCA model to estimate the GHG emissions from the selected case study ferry operated on Thames River, this study indicated the advantages of using a battery-powered propulsion system compared to the conventional one from the point of view of environmental footprint, and particularly on the carbon emission reduction. A UK based cost analysis on the operational phase of the ferry was also carried out to determine the economic benefits of applying battery power system and using electricity generated from renewable sources. A fleet consideration was conducted based on the data from the collaborating ferry operator which broadly illustrated the benefits of adopting battery power plants in the maritime industry especially on inland and short-sea shipping. Therefore, based on these results, the following observations and recommendations are made:

1. Replacing the ferry's conventional system by battery power plant can reduce the life cycle environmental impact (GHG emissions) by around 30% in 2019 and 86% in 2050 but at the expense of higher volumes and increased displacements for the same carrying capacity ;
2. Utilising renewable energy for electricity generation could further decrease the environmental protection potential (GWP) and the economic cost when applying

battery power plant to the selected ferry; the decrement is more than 99% compared to using conventional power system which will fulfil the IMO and UK's targets;

3. The Life Cycle Cost results indicate the battery-powered system can reduce the total life cycle cost by about 15% relevant to conventional power systems; a potential fleet-wide transition to this powering system, indicated significant GHG emission reduction potential;
4. A recommendation is made to UK policymakers to further design the carbon credit to economically incentivise operators to select battery-powered ferries and protect the environment;
5. The approach presented in this study provides a holistic way to evaluate different design alternatives in the early design phase; to meet the challenging target of emission reduction pledged by the UK government, EU and IMO, it is recommended to adopt battery power plants with electricity from renewables on inland and short sea shipping vessels.

Further sensitivity analysis on electricity prices (such as from grid mix and renewable energy) will be carried out. The electricity prices from the UK in the future, EU and the rest of the world can be considered. Also, a holistic life-cycle cost assessment considering all the activities and life stages will provide more confidence and reduce the investment risk for the different stakeholders in the marine industry (shipbuilder, ship operators, port authorities, scrapping shipyards, policymakers and so on).

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AUTHOR CONTRIBUTIONS

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