A Comparative Life Cycle Assessment Study on Environmental Performances between Battery-Powered and Conventional Marine Vessels

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ABSTRACT: International Maritime Organization (IMO) has initialized a new strategy on greenhouse gas (GHG) to reduce 50% of GHG from international shipping by 2050 comparing to 2008. Recently, solutions, like fuel cell and renewable energy, have been proposed by technology providers and ship designers. Battery-powered ship is a solution that can lead to a considerable reduction or even elimination of gaseous emissions, thus limiting fossil fuels consumptions. This paper aims to determine the benefits and drawbacks of marine battery propulsion system by conducting a comparative study using Life Cycle Assessment (LCA). It holistically evaluates the performances of the proposed system and the respective conventional one, applied on a 33-meter-long short-route ferry operating on the Thames. The results indicate the battery-powered system instead of marine engines can reduce the environmental impacts and GHG from ships, which fulfils the IMO requirements and proves the emission control potential of battery-powered systems.

1 INTRODUCTION

International shipping is one of the most efficient transportation means with the largest quantity of cargo transportation and the least air pollution released. According to IMO's report in 2014, the estimation of greenhouse gas emissions from international shipping accounted for only 2.2% of global anthropogenic carbon dioxide emissions. However, to achieve the temperature goal of Paris Agreement and the vision of United Nations'(Committee on Climate Change, 2019), GHG emission from marine sector should be highly addressed and urgent actions are also required to meet IMO's new targets comparing to 2008: 40% and 70% CO_2 reductions in 2030 and 2050 respectively and 50% GHG emission reduction in 2050 (IMO, 2018). There are a series of emission reduction technologies are under investigation and development, such as applications of low sulphur fuel oil, liquefied natural gas and renewable energy, but it is extremely challenging to realize this target from the perspective of time frame and technology maturity (Hwang et al., 2019). Due to the pace of the challenging target, most of the GHG emission reduction technologies are required to be developed rapidly such as the usage of liquefied natural gas as a marine fuel, the development of hydrogen engine, the application of the after-treatment system and all-electric ships. Among these GHG reduction methods, all-electric ships are one promising solution since all-electric cars are practically in-use which provides a solid fundamental for marine applications (Divya and Østergaard, 2009; Vicenzutti et al., 2015).

Recent years, the application of fossil fuels has raised significant concerns due to emission generation during combustion, such as SOx, NOx and CO_2, polluting the environment. The first two air pollutions are main contributors to acidification of the ambition such as the formation of acid rains. According to the revised MARPOL Annex VI, starting from 2020, the global sulphur limit will be reduced from the current 3.50% to 0.50%. From 2015, the limits for SOx and particulate matter released in the Emission Control Areas were reduced to 0.10%. Also, in the ECA region, Tier III NOx standard has become effective on ship build on or after 2016. Regarding CO_2 emission, it is more concerned as the largest contributor in global warming effect than its acidification impact. Although many higher global warming potential gases are existing, CO_2 has become the most significant GHG due to the substantial emission released from the burning of fossil fuels. According to the data collected by the World Bank, in 2014, the annual global CO_2 emission is more than 36 billion tonnes and the other substantial released GHGs are methane and NO_2 which are about 8 billion and 3 billion tonnes in 2012. Therefore, methods and technologies to reduce the carbon dioxide emission (and thus reduce GHG emission) release are attracting to all industries.

Electricity has been used centuries ago onboard ships and it supports the operation of marine systems and equipment, for instance, navigation, lighting, equipment control and cargo handling. However, the majority of sources of ship propulsion power was still coming from marine engines which combust fossil fuels to supply mechanical power and electricity. To replace these engines to get rid of fossil fuels onboard ship, battery-powered ship concept which intends to use electricity from onshore power plants. The battery system has not only avoided emission release during shipping but also considered as a more stable system and the maintenance requirement of the system is lower than engines due to no moving parts in the battery system. The hybrid system, combining engines and batteries, and sometimes other renewable resources, has been investigated for many years (Dedes, 2013; Jeong et al., 2018; Ling-Chin and Roskilly, 2016).

Since electric vehicles have been discussed for many years, many research work has already evaluated the application of different batteries technologies to discover their environmental impacts. Sanfelix et al. evaluated both the environmental and economic performance of the lithium-Ion batteries in 2016 and discovered the manufacturing stage has the highest environmental load for all the considered impact categories (Sanfélix et al., 2016). In 2019, Dai's team has investigated the application of li-ion batteries on electric vehicles which also indicates the main environmental impact contributor of the batteries are from the material and energy use during production (Dai et al., 2019). Any other 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 conclude the most significant contributor to life cycle GHG emission is the cell production phase (Zhao and You, 2019). Matheys has assessed 5 different battery technologies for electric vehicles to indicate the most environmentally friendly one with the best overall environmental impact (Matheys et al., 2009). Similarly, the research carried out in the University of Oldenburg investigated four different stationary battery technologies on their cumulative energy demand and global warming potential. However, the results showed the usage of batteries dominates the life cycle impact which is different from others' research results (Hiremath et al., 2015; Mitavachan, 2014).

In the meantime, the applications of batteries on marine vessels are under development: Kluiters and his research team have tested the application of sodium/nickel chloride battery for ships back to 1999. Due to the limitation of the battery technologies, the advantages of sodium/nickel chloride battery was only proved to be better than sodium/sulphur battery (Kluiters et al., 1999). In the last decade, many pieces of research on batteries technologies are focusing on their application on ships. Lan et al. have carried out one study to investigate the optimal size of a hybrid ship power system combining solar energy, diesel engine and battery system. The result from the research was to minimize the investment and operational costs and the carbon dioxide emissions release of the ship using a hybrid system with the consideration of the solar irradiations and temperature along the voyage (Lan et al., 2015). Misyris' research team also developed an estimation algorithm to illustrate the battery state during the ship operation (Misyris et al., 2017).

To identify and evaluate the performance of the marine propulsion system, life cycle assessment is widely adopted which covers the material exploitation, manufacturing, operation, maintenance and scrapping stages. LCA has been adopted to evaluate the performance of Thai Island's diesel/PV/wind hybrid microgrid from the perspective of environmental sustainability (Smith et al., 2015). There is also application 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, 2014). There are also many applications of LCA on battery system evaluations and all the previously mentioned researches on battery system in automobile industry applied LCA methodology to assess and compare their environmental impacts (Dunn et al., 2016).

However, although there are several pieces of research on the evaluation of battery technologies on marine vessels, it is still lack of investigation either from the point view of using a battery as an only power source or applying holistic analysis such LCA approach. It is necessary to determine the performance of a battery-powered vessel comparing to a conventional vessel from the perspective of environmental friendliness to address the advantages of electric vessels.

2 METHODOLOGY

ISO standard has provided comprehensive procedures to carry out an LCA analysis and basically, LCA method can be carried out by following four phases: a) Goal and scope definition, b) Life cycle inventory analysis, c) Life cycle impact analysis and d) Life cycle interpretation (ISO, 2006).

2.1 Goal and scope definition

In goal and scope definition phase, the target of this LCA investigation will be identified first which could be a product, a system; a technology or a strategy. Then the reasons behind the investigation should be clarified, e.g. most studies are aiming to find out the environmental impacts of the target and sometimes only one or several interesting impacts are under considerations. The reasons for the study sometimes can be determined according to the audiences and their interests so that the objective of the study could be adapted accordingly.

The study scope will be determined by identifying the product's main functions, tightly connected activities and their inputs and outputs, impact assessment method selection, and associated data collection, assumption and quality check. As a fact, an ideal LCA assessment should be boundless who has no defined scope and modelling every single activity during the target's life span. However, a boundless study requires support from many industries and it becomes time-consuming to collect data. Since the objective sometimes focuses inside one or a few industries, the boundary could be determined and help to restrict the never-ending data collection process. Furthermore, to restrict the scope is not only to accelerate the study but also due to the data availability, such as lack of data recording, difficulty to retrieve data from other industry and sometimes confidential issues. Therefore, at the beginning to the study, the goal and scope should be well defined and this definition phase will provide a focused point and an overall view of the LCA study and model which will help to determine the data required in next phase.

2.2 Life cycle inventory analysis

In this analysis, an inventory of emissions will be developed based on the LCA model and data requirement established in the goal and scope definition phase. In the marine industry or shipbuilding industry, data required are usually the vessel specification, operational profiles and maintenance plans, with which a preliminary design could be conducted. However, the LCA model will not be focused only inside the marine industry and the material exploitation, transportation, manufacturing and many other processes should be involved to develop a comprehensive LCA assessment. These data will be collected and based on relevant formulas, the emissions quantities could be eventually calculated which will be used to develop the emission inventory.

In this phase, the goal and scope of the LCA study could be refined because sometimes the data requirement is different from what was defined in the goal and scope definition phase. For example, the raw material exploitation data may be difficult to derive, some emission categories could be less interesting in different industry and sometimes more activities are found to be available during the data collection and calculation. The output of this phase will be an emission inventory (LCI) covering a list of emissions with their quantities in the selected environmental categories. This inventory will be categorized and characterized in the next phase to determine the environmental impact of the target.

2.3 Life cycle impact analysis

This phase will be divided into three steps: a) selection: to select environmental categories; b) classification: to assign emissions from the inventory to different categories; c) characterization: convert/transform emissions assigned to the categories into the indicator of its group. The detailed processes are presented in Figure 1.

In the selection step, impact categories will be selected based on the goal of the study. For each category selected, there will be an emission indicator which is usually the most common emission in the categories. For different characterization model, it has a different indicator selector. For CML model as an example, carbon dioxide is the indicator for global warming potential, sulphur dioxide for acidification potential, phosphate for eutrophication potential.

After selection, all the inventory results will be assigned to different impact categories. One emission could contribute more than one emission impact. An example is given in Figure 1 and example emissions are presented under different categories.

The last step will convert all the assigned emission in one category into the indicator based on the factors provided in the characterization model. Figure 1 provides an example of conversion factors using CML model.

This is also the phase of considering the sensitivity and uncertainty of data collected or factors involved. Sensitivity analysis is a way to investigate how variations in input values or assumptions affect the model outputs. When the data or factors varied significantly in the past, it will help to determine the impact of variation on the assessment results. Uncertainty treatment is used when limited knowledge is available to exactly describe the existing state or possible outcome. Under certain circumstances, data or factors will be based on assumptions, such as the engineer's judgement, as it is difficult to determine an exact value. Uncertainty treatment could apply possible distributions of the data or factor to find out the trust level.

After the phase of LCIA, the final step will be the interpretation of all phases.

2.4 Interpretation phase

The final phase of the LCA assessment is to deliver results obtained through the study based on the inventory and impact assessment. This phase will also conclude the LCA study and provide suggestions to the participants such as manufacturers, operators, and decision-makers.

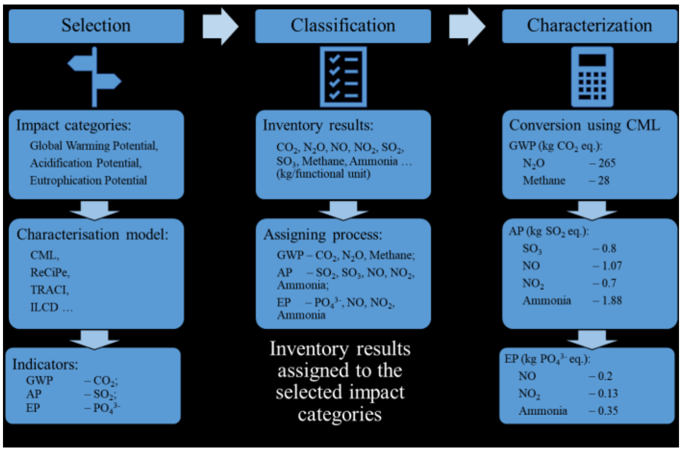

Figure 1 Processes of Life cycle impact analysis

3 CASE SHIP STUDY

This paper will investigate a planned short route ferry operated in Thames River, London. This ferry will be powered by electricity only instead of the traditional propulsion system to get rid of fossil fuel consumption on board and to avoid the emission during ship operation. In this section, the data collection will be presented which will be used to support the development of LCA model and the LCA assessment. The specification of the case ship is shown in Table 1 and the route of the vessel is presented in Figure 2. The route of the ferry is along the Thames, servicing between Westminster and Woolwich and stopping at London Eye, Embankment, Blackfriars, Bankside, London Bridge, Tower, Canary Wharf, Greenland (Surry Quays), Masthouse Terrance, Greenwich, North Greenwich. The service hours are about 18 hours per day and battery power system is considered to be applied. This study will identify the performance of the battery power system and determine its advantages comparing to traditional propulsion system (diesel engines).

Table 1 Case ship specification

Main particulars			
LOA (m)	35	Block coefficient (-)	0.582
LBP (m)	32.538	Midship coefficient (-)	0.849
Breadth (m)	8	Prismatic coefficient (-)	0.69
Depth (m)	2.354	Waterplane coefficient (-)	0.842
Draught (m)	1	Geometric displacement (t)	75
No. of engines	2	Engine power (kW)	625
Battery type	Li-ion	Battery capacity (kWh)	650

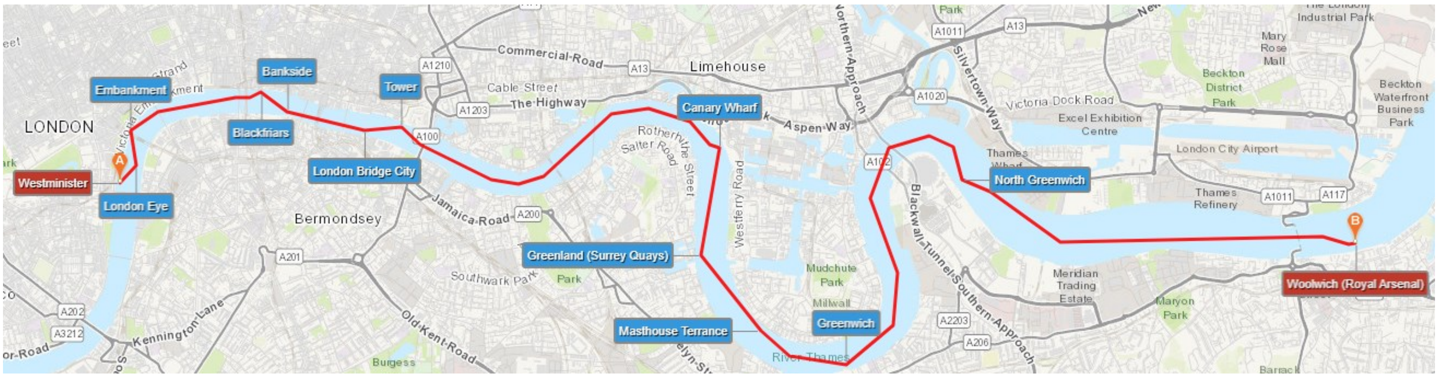

Figure 2 Case ferry route

3.1 *Case scenarios*

Two different propulsion systems will be under consideration so that two different case scenarios are developed: 1) application of diesel engines; 2) application of battery power system.

3.1.1 *Case 1- Use a diesel mechanical system*

This case scenario applies traditional propulsion system which equips with two diesel engines. The ferry will be operated 18 hours per day. A round trip will be 3.6 hours and the idling time at destinations will be about 0.35 hours (21 minutes).

3.1.2 *Case 2- Use a battery power system*

In this scenario, the diesel engine will be replaced by a battery power system with the same power loads. The usage of electricity will take the place of diesel oil so the emissions from ferry operation will be eliminated but the upstream emission from the electricity generation must be taken into account.

3.2 *Preliminary analysis*

Based on the data provided by Thames Clipper, the power requirement of a similar ferry operated in the same route is derived (Figure 3, Figure 4 and Figure 5). Based on the power requirement presented in Table 2, the weights and costs of different types of battery packs could be determined according to Table 3.

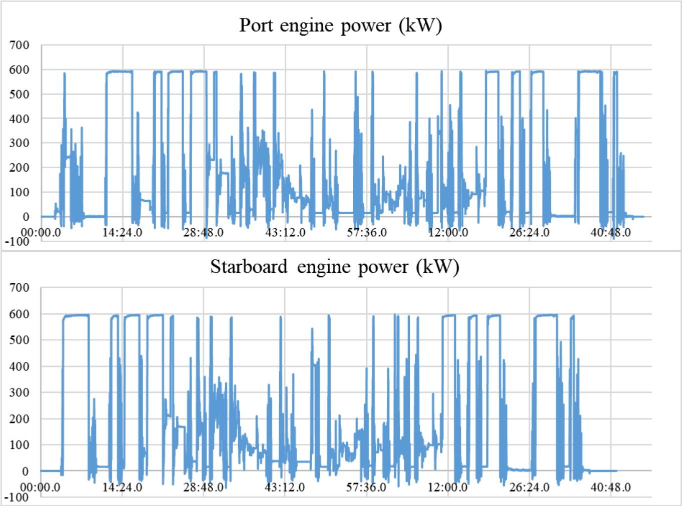

Figure 3 Port and starboard engine power outputs

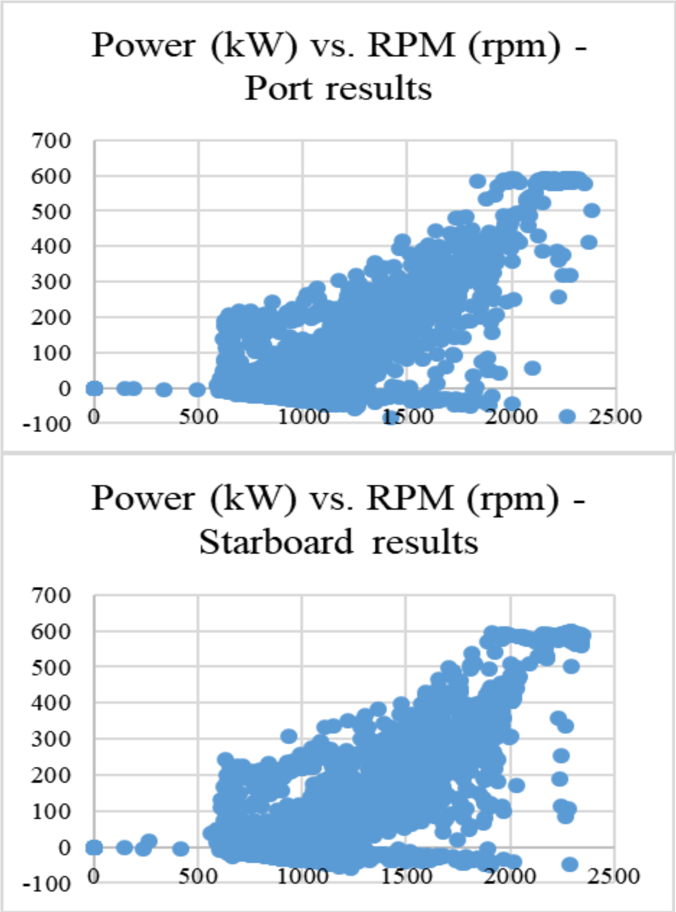

Figure 4 Engine power output under different RPM

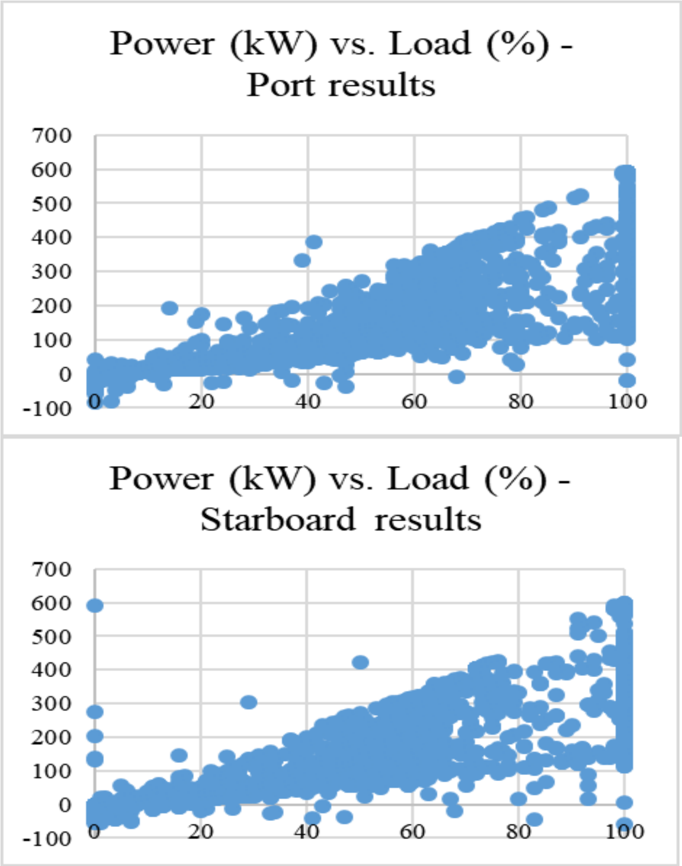

Figure 5 Engine power output under different loads

Table 2 Engine energy requirement, fuel oil consumptions and emission releases

Stbd. engine	Port engine	Total
Total propulsion energy (kWh)		
319.97	329.74	649.7
Total fuel (l)		
82.79	86.20	168.98
Total fuel energy (kWh)*		
834.65	869.01	1703.67
Efficiency (-)		
0.38	0.38	
Total CO_2 (t)		
0.27	0.28	0.55
NOx (kg)		
3.84	3.96	7.80

* Low heating value of fuel is 42700kJ/kg

Table 3 Battery types, costs and energy-weight relations (Galloway and Dustmann, 2003; Linden et al., 2002)

Type	Wh/kg	Cost ($/kWh)	Cost ($/kg)
Lead-acid	35	90	3.2
Vanadium Bromine	50	300	15
Silver Cadmium	70		
Zinc Bromine	70		
Sodium/Nickel-Chloride	115	110	12.7
Lithium-Ion	150	600	90

4 LIFE CYCLE ASSESSMENT

This section will present the LCA analysis on the short route ferry under two different scenarios. The approach from section 2 will be followed.

4.1 Goal and scope

The goal of this LCA study is to determine the environmental impacts of two different power systems on marine vessels (ferry in this case). The benefits of applying battery power system will be derived by comparing with engine power system from the perspective of environmental impacts. Usually, the life phases of on-board power system include five phases (Figure 6): material exploitation, system manufacturing, utilization phase, maintenance periods and end of life. Under different phases, associated material, energy and emissions will be under consideration and shown in Figure 7(for further study, cash flow will be considered). To retrieve the material, energy and emission flow, main activities under these phases should be identified and associated data are required for LCA study.

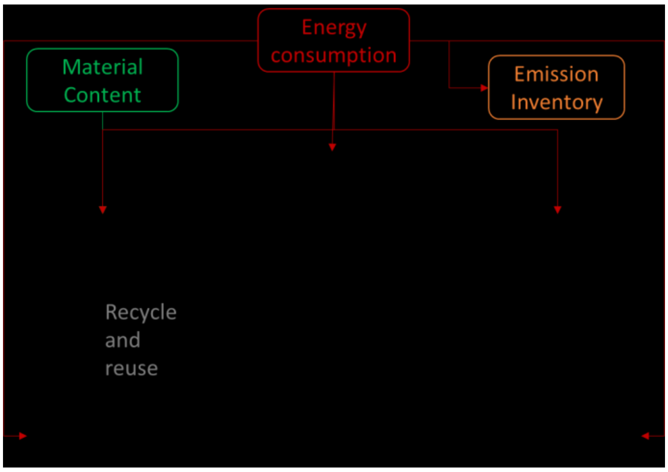

Figure 6 Life cycle stages and interactions

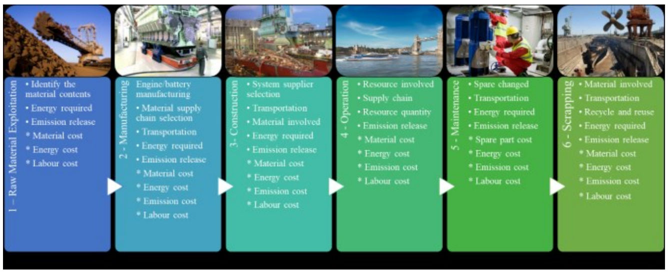

Figure 7 Flow chart of life cycle activities and data collection master checklist

To simplify the method, a series of assumptions are made based on engineers' judgement and industry's practices:

A) The ship is planned to be built in the UK; the equipment of the propulsion system will be supplied by Wartsila and Corvus (Corvus, 2019; Wartsila, 2020);
B) The raw materials of battery and engines come from exploitation in the same area;
C) Costs and impacts of charging stations will not be considered in this study;
D) The assumption is made that all the rest parts of the vessel remain unchanged when replacing diesel engines with battery packs. Since the differences between the two cases are only the propulsion/power systems, the comparison and evaluation focus on these systems;
E) As the growing attention on global warming effect, this study will investigate the impact of power systems on the global warming potential of the ferry; in this study, CML 2001 are selected to characterise the emissions in the life cycle inventory (CML, 2016);
F) The fuel oil consumption is determined using data provided by shipowner and ship operator which has shown and determined in the previous section;
G) Emission generated from diesel engines running and electricity required by battery packs are estimated using the following equations:

d.1.) Emission generation

$$M_E = FOC \times CF \qquad (1)$$

where, M_E is the quantity of one specific emission from fuel combustion; CF is the carbon conversion factor provided by IMO.

d.2.) Electricity required from battery packs

$$E_B = FOC \times LHV \times r \qquad (2)$$

where, E_B is the electricity required for battery packs; r is the overall efficiency of using electricity including charging from shore power and onboard utilization.

H) OpenLCA is used to model the life cycle processes of the ship power system (Figure 8) (Ciroth et al., 2020).

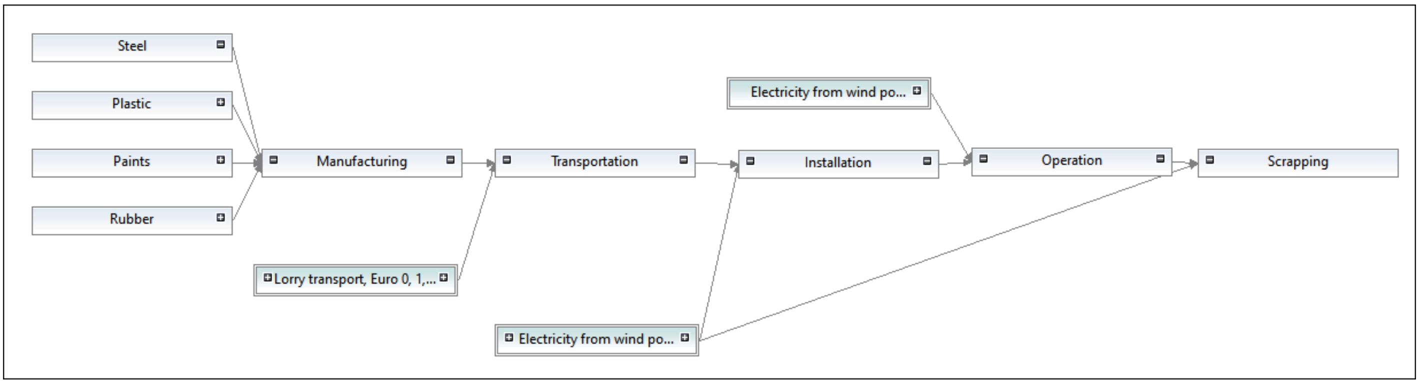

Figure 8 Life cycle modelling of the ship power system

4.2 *Life Cycle Inventory Assessment*

With the help of software OpenLCA and its database, the following emission inventory is developed which are trailered to the emission of interest in Table 4

Table 4 Life cycle emission inventory.

Emission	Category	Result (kg)
Ammonia	Air	65.17
Carbon dioxide	Air	4.34E+7
Dinitrogen monoxide	Air	105.12
Methane	Air	44649.40
Nitrogen dioxide	Air	13234.07
Nitrogen monoxide	Air	0.63
Sulphur dioxide	Air	24733.96
Sulphur trioxide	Air	7.46E-08
Ammonia	Soil	0.010
Phosphate	Soil	0.0092
Ammonia	Water	1.87
Phosphate	Water	20.96
Ammonia	Water	2.75E-05
Phosphate	Water	0.00073

4.1 *Life Cycle Impact Assessment Results*

This section will present the results of characterizing the emissions in LCI by applying CML characterization model. The results are determined not only considering the emission mentioned in the inventory in this paper but also many other insignificant and low quantity emissions included in the OpenLCA database. The comparison of results between ferry with diesel engines and battery system is presented in Table 5. From the table, it is observed that with the battery system as the propulsion system on the ferry instead of diesel engines, the global warming potential is reduced by around 25%.

4.2 *Detail discussion (sensitivity analysis)*

Since the battery power ferry could reduce 25% of GHG emissions, it is still challenging to achieve the target of reducing 40% of carbon dioxide (CO_2) by 2030 and 50% of the GHG emission release by 2050. The main source of the GHG emissions from the life span of battery power ferry comes from the electricity generation process which, in this analysis, uses supply from grid mix in the UK. It is a mix of many different energy sources for electrical power generation which includes fossil fuel consumptions, such as hard coal, natural gas, fuel oil and so on. In this section, the impact of using different energy sources for electricity generation will be investigated.

Two energy sources of electricity are under consideration: hydropower and wind power and the results are compared with previous results (engine using diesel oil and battery using grid mix electricity). The comparison results are shown in Table 6. From the results, the observation is that around 99% of GHG emission has been avoided if using renewable energy as electricity source either comparing to using diesel engines or battery system supplied by grid mix electricity on the ferry.

Table 5 Global warming potential comparison

Global warming potential (GWP) (kg CO_2 eq.)	
Ferry with diesel engines	4.46E+07
Ferry with a battery system	3.31E+07

Table 6 GWP potential and reduction comparison.

GWP (kg CO_2 eq.)		Reduction Rate
Diesel oil	4.46E+07	Benchmark
Electricity (grid mix)	3.31E+07	25.78%
Electricity (hydro)	4.10E+05	99.08%
Electricity (wind)	3.11E+05	99.30%

5 CONCLUSION

This study investigated the performance of applying battery power system on a short ferry from the perspective of environmental protection especially to the global warming contributions. LCA approach is applied to holistically consider all the essential life processes and activities in the ferry's life span, covering the production of the system, construction, operational and scrapping phases. An LCA model is established in OpenLCA software to take all these phases and activities into account and an LCI inventory is established to cover all the emissions from the targeted emission categories. Eventually, after characterization of the LCI results, a comparative study was carried out to compare the result from different power system candidates. It was derived that comparing to the traditional power system with diesel engines (consuming fossil fuels), the ferry with battery system could achieve about one-fourth of GHG emissions reduction whose electricity supply is from grid mix. However, due to the challenging emission reduction target from IMO, two more considerations of electricity from two other sources are made: hydro and wind power. The reduction rate could be reached about 99% comparing to using diesel engines on the ferry which reduce the GWP from 45 thousand tons CO_2 eq. to 410 and 311 tons CO_2 eq. Hence this paper has developed an LCA model to estimate the emission from a selected ferry and the model also helped to determine the advantage of using battery power systems on the ferry from the point view of emission reduction. Recommendations are made to apply renewable energy for electricity generation to further dig the environmental protection potential of applying the battery system in the marine industry.

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REFERENCE

Ciroth, D.A., Noi, C. Di, Lohse, T., Srocka, M., 2020. openLCA 1.10 Comprehensive User Manual.

CML, 2016. CML-IA Characterisation Factors - Leiden University [WWW Document]. Inst. Environ. Sci. URL https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors (accessed 6.9.20).

Committee on Climate Change, 2019. Net Zero: The UK's contribution to stopping global warming 277.

Corvus, 2019. Corvus Dolphin Energy.

Dai, Q., Kelly, J.C., Gaines, L., Wang, M., 2019. Life cycle analysis of lithium-ion batteries for automotive applications. Batteries 5. https://doi.org/10.3390/batteries5020048

Dedes, E.K., 2013. Investigation of Hybrid Systems for Diesel Powered Ships By. Soton 324.

Delogu, M., Zanchi, L., Maltese, S., Bonoli, A., Pierini, M., 2016. Environmental and economic life cycle assessment of a lightweight solution for an automotive component: A comparison between talc-filled and hollow glass microspheres-reinforced polymer composites. J. Clean. Prod. 139, 548–560. https://doi.org/10.1016/J.JCLEPRO.2016.08.079

Divya, K.C., Østergaard, J., 2009. Battery energy storage technology for power systems-An overview. Electr. Power Syst. Res. https://doi.org/10.1016/j.epsr.2008.09.017

Dunn, J.B., Gaines, L., Kelly, J.C., Gallagher, K.G., 2016. Life cycle analysis summary for automotive lithiumion battery production and recycling. REWAS 2016 Towar. Mater. Resour. Sustain. 73–79. https://doi.org/10.1007/978-3-319-48768-7_11

Galloway, R.C., Dustmann, C.H., 2003. ZEBRA Battery-Material Cost Availability and Recycling, in: EVS 20, 20th International Electric Vehicle Symposium and Exposition, Powering Sustainable Transportation, Conference Proceedings, Long Beach, US, Nov 15-19, 2003. pp. 1–9.

Hiremath, M., Derendorf, K., Vogt, T., 2015. Comparative life cycle assessment of battery storage systems for stationary applications. Environ. Sci. Technol. 49, 4825–4833. https://doi.org/10.1021/es504572q

Hwang, S., Jeong, B., Jung, K., Kim, M., Zhou, P., 2019. Life cycle assessment of lng fueled vessel in domestic services. J. Mar. Sci. Eng. 7, 1–25. https://doi.org/10.3390/jmse7100359

IMO, 2018. I:\MEPC\72\MEPC 72-17-ADD.1.docx 304, 1–11.

ISO, 2006. ISO 14040:2006 - Environmental management -- Life cycle assessment -- Principles and framework [WWW Document]. Int. Organ. Stand. Geneva, Switz. URL https://www.iso.org/standard/37456.html (accessed 7.18.18).

Jeong, B., Wang, H., Oguz, E., Zhou, P., 2018. An effective framework for life cycle and cost assessment for marine vessels aiming to select optimal propulsion systems. J. Clean. Prod. 187, 111–130. https://doi.org/10.1016/J.JCLEPRO.2018.03.184

Kluiters, E.C., Schmal, D., Ter Veen, W.R., Posthumus, K.J.C.M., 1999. Testing of a sodium/nickel chloride (ZEBRA) battery for electric propulsion of ships and vehicles. J. Power Sources 80, 261–264. https://doi.org/10.1016/S0378-7753(99)00075-0

Lan, H., Wen, S., Hong, Y.Y., Yu, D.C., Zhang, L., 2015. Optimal sizing of hybrid PV/diesel/battery in ship power system. Appl. Energy 158, 26–34. https://doi.org/10.1016/j.apenergy.2015.08.031

Linden, D., Reddy Editor, T.B., York, N., San, C., Lisbon, F., Madrid, L., City, M., New, M., San, D., Seoul, J., 2002. HANDBOOK OF BATTERIES.

Ling-Chin, J., Roskilly, A.P., 2016. Investigating the implications of a new-build hybrid power system for Roll-on/Roll-off cargo ships from a sustainability perspective – A life cycle assessment case study. Appl. Energy 181, 416–434. https://doi.org/10.1016/J.APENERGY.2016.08.065

Matheys, J., Timmermans, J.M., Van Mierlo, J., Meyer, S., Van Den Bossche, P., 2009. Comparison of the environmental impact of five electric vehicle battery technologies using LCA. Int. J. Sustain. Manuf. 1, 318–329. https://doi.org/10.1504/IJSM.2009.023977

Misyris, G.S., Marinopoulos, A., Doukas, D.I., Tengnér, T., Labridis, D.P., 2017. On battery state estimation algorithms for electric ship applications. Electr. Power Syst. Res. 151, 115–124. https://doi.org/10.1016/j.epsr.2017.05.009

Mitavachan, H., 2014. Comparative Life Cycle Assessment of Stationary Battery Storage Technologies for Balancing Fluctuations of Renewable Energy Sources. Thesis 103.

Raugei, M., El Fakir, O., Wang, L., Lin, J., Morrey, D., 2014. Life cycle assessment of the potential environmental benefits of a novel hot forming process in automotive manufacturing. J. Clean. Prod. 83, 80–86. https://doi.org/10.1016/J.JCLEPRO.2014.07.037

Raugei, M., Morrey, D., Hutchinson, A., Winfield, P., 2015. A coherent life cycle assessment of a range of lightweighting strategies for compact vehicles. J. Clean. Prod. 108, 1168–1176. https://doi.org/10.1016/J.JCLEPRO.2015.05.100

Sanfélix, J., de la Rúa, C., Schmidt, J.H., Messagie, M., Van Mierlo, J., 2016. Environmental and economic performance of an li-ion battery pack: A multiregional input-output approach. Energies 9. https://doi.org/10.3390/en9080584

Smith, C., Burrows, J., Scheier, E., Young, A., Smith, J., Young, T., Gheewala, S.H., 2015. Comparative Life Cycle Assessment of a Thai Island's diesel/PV/wind hybrid microgrid. Renew. Energy 80, 85–100. https://doi.org/10.1016/J.RENENE.2015.01.003

Vicenzutti, A., Bosich, D., Giadrossi, G., Sulligoi, G., 2015. The Role of Voltage Controls in Modern All-Electric Ships: Toward the all electric ship. IEEE Electrif. Mag. 3, 49–65. https://doi.org/10.1109/MELE.2015.2413437

Wartsila, 2020. TrAm project report.

Zhao, S., You, F., 2019. Comparative Life-Cycle Assessment of Li-Ion Batteries through Process-Based and Integrated Hybrid Approaches. ACS Sustain. Chem. Eng. 7, 5082–5094. https://doi.org/10.1021/acssuschemeng.8b05902