Live-Life Cycle Assessment of the Electric Propulsion Ship using Solar PV

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ABSTRACT

This paper was born to introduce a novel methodology termed Live-Life Cycle Assessment using a simulation-based data generation technique that can remedy the inherent shortcomings of conventional practices of lifecycle assessment. To demonstrate its excellence, the proposed method was applied to one of the most challenging topics in the marine industry. That was to tackle the fundamental doubt of whether solar-electric propulsion ships could truly be the future energy solution of maritime transports by fulfilling new environmental conventions and goals around the world. The case study began with an existing hybrid short route ferry running on diesel and plug-in battery power. Credible PV systems for the case ship was modelled to produce ship performance data under various operational/environmental circumstances of the coastal zones across 29 countries in the platform of MATLAB/Simulink. As a key functionality of Live-Life Cycle Assessment, the produced data was directly fed, as inputs, into life cycle assessment to avoid conventional practices that heavily rely on outdated data libraries. Results of the case study clearly revealed and quantified the correlations of the performance of PV-battery systems with climate parameters such as temperature and irradiance of subject areas as well as national power production methods. For example, in terms of Global Warming Potential, the case ship with the PV system was estimated to reduce 40,812 kg CO_2 eq. per year in Brazil (average temp.: 27.4 , major energy source: hydro). Interestingly, the same vessel was found to achieve greater reductions in India (average temp.: 27.5 , major energy source: coal) or Australia (average temp.: 20.1 , major energy source: coal) where are overly laden with coal-based power plants. Therefore, their reduction levels were estimated at 152,887 kg CO_2 eq. per year and 141,517 kg CO_2 eq. per year respectively. This paper clearly shows the excellence of the proposed method to demystify/quantify the impacts of parametric variables on the performance of the PV-electric ship. Moreover, it highly suggests the Live-Life Cycle Assessment could be a solution as a new standard to respond to strong demand to obtain general observation of lifecycle benefits/harms of new technologies across all industries, not necessarily limited to the maritime sector.

Keywords: *Life Cycle Assessment, Live LCA, Electric propulsion ship, Solar PV, LLCA, Decarbonising shipping*

ABBREVIATIONS and TERMS

AMP	Alternative Maritime Power
AP	Acidification Potential
CH_4	Methane
CI	Cold-ironing
CO	Carbon Monoxide
CO_2	Carbon dioxide
CO_2 eq.	Carbon dioxide equivalent
DP	Dynamic Positioning
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EP	Eutrophication Potential
EPS	Electric Propulsion Ship
ESS	Energy Storage System
GHG	Greenhouse Gases
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MLC	Multilevel Converter
MPPT	Maximum Power Point Tracking
N_2O	Nitrous Oxide
NMVOC	Non-methane Volatile Organic Compounds
NOx	Nitrogen Oxides

ODS	Ozone Depleting Substances
PM	Particulate Matters
POCP	Photochemical Ozone Creation Potential
PV	Photovoltaic
SFOC	Specific Fuel Oil Consumption
SO_2 eq.	Sulphur dioxide equivalent
SO_X	Sulphur Oxides
SOC	State of Charge

1. Introduction

1.1. Maritime environmental concerns

Worldwide trade has increased dramatically during the last centuries, paralleling the continuous growth of global GDP, as illustrated in Figure 1 (a) and (b) [1, 2]. Given that the waterborne transportation accounts for approximately 90% of worldwide trade [3-6], the number and size of marine vessels have also significantly grown during the same period of time (see Figure 1 (c) and Figure 1 (d)) [1, 7]. As a result, shipping has become the fourth-largest sector contributing to climate change: about 14% of world greenhouse gases (GHGs) are produced from shipping activities [8]. According to the data compiled from 2007 to 2018, the world shipping has produced around 3 % of CO_2 emissions, as well as approximately 15% and 13% of global NO_x and SO_x emissions, respectively [9, 10].

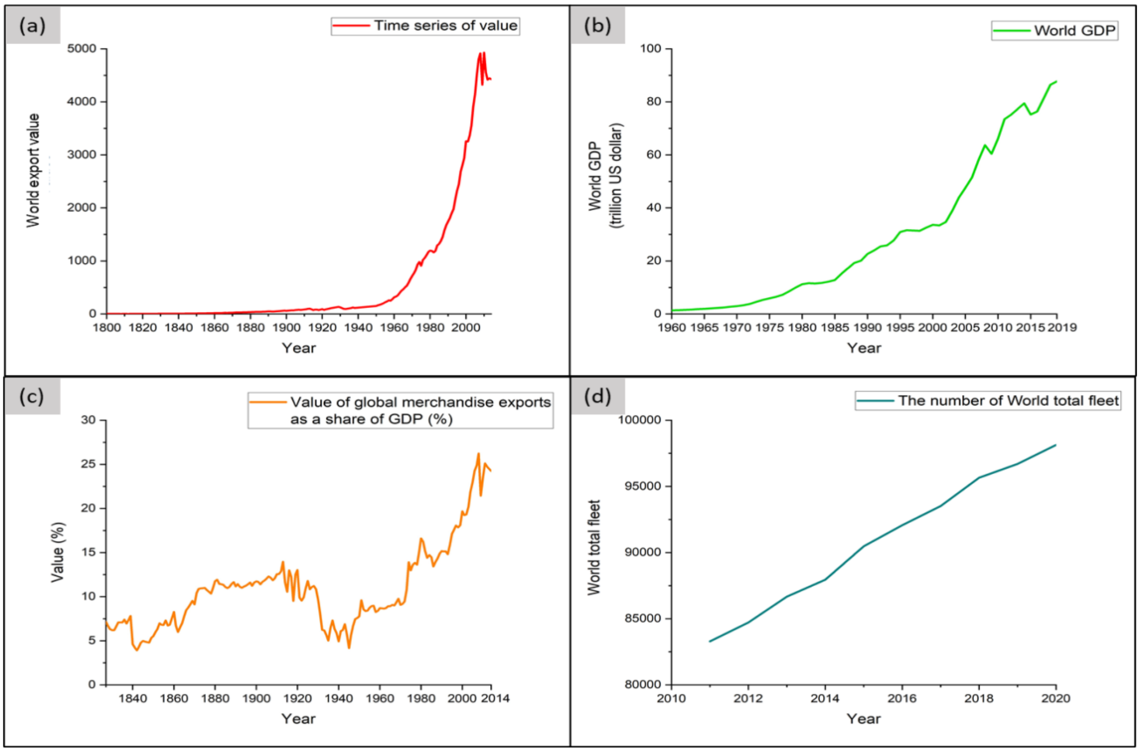


Figure 1. Various graphs; (a) World exports at constant prices, relative to 1913 (world export volumes indexed at 1913=100), (b) World GDP, (c) Ratio of global trade to world GDP, (d) World total fleets.

To preserve our planet, International Maritime Organisation (IMO) has enacted and implemented a series of stringent environmental regulations to reduce air pollutants that contribute to global warming, acid rain and even more. In particular, IMO MARPOL Annex VI contains regulations on curbing air pollution from ships including sulphur oxides (SO_x), nitrous oxides (NO_x), and ozone depleting substances (ODS) [11]. These regulations are continuously reviewed and enhanced through the IMO Marine Environment Protection Committee (MEPC). Moreover, the organisation proposed, in 2018, ambitious and progressive strategies to reduce GHG emissions by at least 40% by 2030 and 70% by 2050 compared to the 2008 emission level [12].

To satisfy those environmental targets, the shipping sector has been urged to achieve the energy transition from conventional oil products to carbon-neutral fuels; as a result, electric-battery and fuel cell systems using alternative fuels like hydrogen, ammonia and methanol are currently in the spotlight. Given that both fuel cell and battery technologies are used to convert primary energy sources into electricity, the popularity of electric propulsion ships, compared to conventional mechanical propulsion ships, is anticipated to grow sharply in the not-too-distant future.

1.2. Holistic environmental impacts of PV Electric ships

Electric propulsion ships using novel electric technologies - such as batteries, solar panels, fuel cells - have drawn great attention and expanded their share into the shipping market gradually [13]. As recognised green maritime solutions [14, 15], those ships are believed to be able to respond to the current demands of maritime environmental protection [16-18] in addition to various benefits as summarised: higher energy efficiency [19], optimisation of engine room arrangement [20, 21] with less volume and weight [22], lower operation and maintenance costs

[23], high system reliability [19] as well as excellent manoeuvrability [17, 24] with remarkable technical advancement [19].

On the other hand, to achieve zero-carbon shipping, solar PV systems with higher technical maturity have started to be considered as a main source of power for marine vessels. In fact, the solar PV system has continued to expand its use and increase its installed capacity due to eco-friendly energy policies and the growing awareness of environmental protection. However, due to the feature of the ship, it has been mainly installed and used on land rather than ships due to the loading of cargo and the limitation of the installation space on the deck. In order to use this system more effectively, research on cost-benefits [25], optimization of the residential solar system [26], and research to investigate the efficient installation status of solar panels [27] have been conducted. In addition, studies on the efficient use of energy storage devices such as lithium batteries with the solar PV system was conducted [28], and a hybrid power generation system including those with diesel generators was also performed [29]. However, through the development of technology and various studies, recent attempts to apply and utilize the solar PV system to ships are continuing.

Solar energy is subject to challenges as power generation is highly dependent on environmental conditions [26, 30, 31] and it may be difficult to secure enough space for PV systems onboard [27]. Given this, the current application of solar-powered ships is due limited to small and short route vessels rather than ocean-going ships. In particular, technical/economic advantages were found for small-scaled PV powered ships [25] with a short payback time through fuel savings [32]. In addition, compared to other renewable technologies, the weight of solar panels is light and easy to apply [33]. Hence, hybrid electric ships fitted with diesel generators, batteries or solar PV panels are presently becoming a new shipbuilding trend for green short sea shipping [28, 29, 34, 35].

Despite recent popularity, PV-powered ships are still at their early stage and several studies have attempted to address technical challenges such as energy storage, infrastructure for electric charging and demands on high power capacity to propel ships, etc [36, 37]. Here are some representative examples. Lim et al. [38] conducted a prediction of electric power consumption on electric propulsion ships to determine the capacity of the generator and propulsion motor. Hansen et al. [39] studied the onboard DC grid system, and Thantirige et al. [40] examined multilevel converter (MLC) topologies that are suitable for medium voltage drives. In addition, Hou et al. [41] contributed to mitigating frequent power fluctuations due to changing propulsion motor load and external factors on electric propulsion ships. In addition, Table 1 summarizes remarkable studies on the combination of electric propulsion systems with PV systems for marine application. This synopsis presents that although electric propulsion ships and the solar PV system have been applied to the maritime sector under the pretext of environmental protection as greener shipping, past studies have due largely focused on only the technical demonstration of the proposed system.

Table 1. Literature review of ships using Solar PV

Ref.	Main Subject & Outcome	Methodology	Power source	Key point
[34]	Battery bank enables a stable power supply. With grid-connected inverters, the hybrid PV/diesel green ship can be an efficient way to supply power to the island from the land.	Shipboard test with Labview program	Solar PV panel, Diesel generator	Power stabilisation, Economic
[42]	Solar PV system applying to the ship can make a reduction in fuel consumption. Cost-effectiveness of the PV system depends on fuel price and the vessel sailing route.	Cost-benefit analysis	Solar PV panel	Cost
[43]	The battery system can be a solution of stabilising for energy supply by Solar PV. Constant power supply by Solar PV is difficult due to changing weather.	Shipboard test	Solar PV panel, Diesel generator	Power stabilisation
[44]	Through sun tracker system, solar PV panel can provide 25 to 50% more energy compared to fixed panel.	dual axis sun trackers system	Solar PV panel, Diesel generator	Efficiency
[45]	There is an environmental improvement by configuring a ship using Solar PV. An additional device to receive electricity from the grid on the land needs to be installed because the capacity of Solar panels is not enough to operate the ship.	Rhino3D and Orca3D software packages, PVSyst 6.0 software, and CML 2000 methodology	Solar PV panel, Energy storage system	Environment, Additional utilization plan
[46]	Comparing the results of simulation between the conventional power ship and the ship integrate solar power system. When the Solar PV system is applied with energy storage devices to the ship, it is helpful to reduce emission.	PSCAD / EMTDC simulation software	Solar PV panel, Diesel generator	Environment, Economic
[47]	Suggesting the algorithm to find the ideal size of Solar PV system, ESS and Diesel generator	Multi-Objective Particle Swarm Optimization (MOPSO)	Solar PV panel, Diesel generator, Energy storage system	Proper sizing of devices
[48]	Route optimization is very important for energy efficiency. For solar ship, meteorological factor is the main thing to consider.	Route optimization based on genetic algorithm	Solar PV panel	Efficiency
[49]	Contributing to layout out of large-scale Solar PV panels and MPPT controlling method on ship.	Designing topology structure of the solar panel array and algorithm of MPPT	Solar PV panel, Energy storage system	Structure, Efficiency
[50]	Applying solar energy system to ship can cut by 4.02% of fuel consumption and by 8.55% of CO2 in a year.	Designing a hybrid power system and verifying the result through the actual test on the ship.	Solar PV panel, Diesel generator, Energy storage system	Verifying the reduction
[51]	Fuzzy logic energy management strategy can contribute to improving power system and fuel saving.	Designing fuzzy logic and verifying it by test on the ship	Solar PV panel, Diesel generator, Energy storage system	Introducing a new strategy
[52]	Solar based hybrid ship using cold-ironing (CI) system can save more energy than that without CI. By optimal energy scheduling, fuel consumption by diesel generator can be reduced.	Calculating the consumption and comparing for each case.	Solar PV panel, Diesel generator, Energy storage system	Cost, Environment
[53]	Conducting analysis of cost benefit by location in route. Through weather forecasting, it is possible to find the best way to produce more electricity by solar PV panels in the route.	Comparing solar irradiance by location	Solar PV panel, Diesel generator	Cost, Geographic impact

Meanwhile, there is no doubt that there has a strong demand for moving toward carbon-neutral fuels for the protection of our planet. However, carbon-free fuels are in the early stages of development in the global shipping sector, and there are a number of different views and outcomes on how these fuels can be produced, distributed, and used onboard for the clean shipping economy [54, 55]. In the same line with this, the electricity from renewable energy sources also contributes to air pollutants unavoidably during the process of manufacturing solar photovoltaic (PV) panels, wind turbines, etc to some extent. [56].

PV-electric ships that run on the electricity from the PV systems onboard and also from the national grid if PV systems are not able to fully cover the required power. The holistic environmental impacts on electricity generation vary greatly depending on primary energy resources, technologies and geographic conditions [54], implying that the same PV electric ship can make totally different environmental performances. This argument can raise a fundamental question to be answered; whether PV-electric ships can ultimately be a future lifecycle solution for world maritime environmental protection with no exception, or whether the same ship can be more harmful than helpful in the environment under some circumstances. Unfortunately, there was no past research that could offer some meaningful insight into this question while a few past studies managed to conduct a brief discussion on the lifecycle benefits or harms of some electric ships [37, 53, 57, 58].

To achieve the proper use of PV electric ships, the fundamental question should be answered by determining the correlations of the environmental performance of PV electric ships with external circumstances such as national electric grids or geographical conditions from the cradle to grave point of view. A narrow-range appraisal of previous studies may be deceptive as another source of possible pollution from incorrect convictions for these ships. Without lifecycle demonstration, PV electric vessels are more likely to be abused with false convictions and misleading them with the wrong local/global policies and decisions. Hence, this paper is driven by the desire to confirm if PV electric ships may outperform conventional diesel ships overall in a variety of service areas and conditions.

Given that, the past publication as listed in Table 1 and their research trends are clearly indicative of lack of relevant studies on the holistic environmental impacts of PV systems. Despite the strong demand of lifecycle environmental demonstration of all potential marine energy sources, most of past research were falling into the research categories of technical issues such as efficiency, stable electricity supply, and cost, etc. This table not only emphasizes that only the technical aspects of research have been carried out, but also serves as a bridge to mention the importance of research on environmental features, which are the fundamental reason why electric propulsion ships and the solar PV system were introduced into the marine sector.

1.3. Limitations of current Life Cycle Assessment

Life cycle assessment (LCA) is a widely-proven tool to evaluate the environmental impact of a product by collecting information on materials used during the entire life cycle and the energy consumption and emission generated from production, operation and disposal of the product [59]. With no doubt, International Maritime Organisation and its member states currently consider LCA the most reliable tool for determining the holistic environmental impacts of marine vessels.

1.3.1. LCA in the marine industry

Voluminous LCA research since the 1960s have demonstrated the excellence of this method across industries and its recognition and application to the marine industry have also grown over the last decade. Here are some remarkable LCA studies on the marine sector. The

Norwegian University of Science and Technology created a dedicated LCA tool for optimising the ship design in terms of energy efficiency and environmental aspects in 2002 [60], the National Maritime Research Institute of Japan developed LCA software for reliable LCI (Life Cycle Inventory analysis) data of cargo ships in 2005 [61], and Kameyama et al. developed 'LIME' which is a comprehensive life cycle impact assessment (LCIA) methodology in 2007 [62]. In addition to these developments, LCA studies have been carried out in consideration of ship construction, operation, maintenance and dismantling throughout the shipping industry in 2014 [63, 64]. In 2018, Wang et al. [65] emphasizes the importance of LCA application in the marine industry and applied this to the ship hull maintenance strategy.

LCA research has been extended to fuel and power systems used in ships: LCA study on main fossil fuels used in ships [66] and on LNG as ship fuel [67]. Houjeiri et al. investigated LCA on marine fuels produced in Saudi Arabia and compared it to LNG [68]. As for power systems, some remarkable studies were conducted: applying a solar panel to a ferry [69], identifying a greener power system [70]. Ma et al. evaluated the lifecycle performances of scrubber systems [71].

Overall, the series of the past LCA research applied to the marine sector above is strong evidence of the effectiveness of LCA on the fundamental problem of this paper that is to understand the holistic environmental benefits/harms of PV-electric ships. Nevertheless, these studies also clearly expose the inherent limitations of the conventional LCA approach which will be discussed in the next section.

1.3.2. Shortcomings of current LCA approach

Table 2. Limitations of LCA research in the marine sector

Ref	Main subject & outcomes	Specific case / Limitation
[53]	Suggesting an optimal shipping route for merchant vessels equipped with photovoltaic (PV) modules on board	Datasets on solar radiation on shipping routes in the north western Black Sea basin
[58]	Modelling a passenger ship equipped with a diesel engine as a full battery propulsion system and analysing the environmental impact through LCA	Consideration of South Korea's current energy importation and production status
[62]	Developed LCA methodology, called LIME, and performed LCA	Case of a bulk carrier
[64]	Performed LCA for ocean-going ships	Case of an oil tanker
[66]	Calculated the environmental impacts of four different fuels used on ships using LCA	No including alternative and greener fuels
[67]	Performing LCA on LNG fuel compared to MGO	Case of 50K bulk carrier engaged in domestic services in South Korea
[68]	Comparing the GHG emissions of HFO and MGO produced from Saudi crude oil to LNG in different global regions in terms of LCA	Case of Saudi crude oil
[69]	Conducted LCA for a ferry applying a solar panel	Case of operating in the Marmara Sea
[70]	Determining the superiority of power systems from an environmental perspective	Case of operating RoRo cargo ships in ECAs.
[71]	Investigation of GHG emission of ships with and without scrubber system	Assuming engine road
[72, 73]	Development of a methodology that can estimate the approximate emission amount only with engine power and ship age	Setting engine load as a full power

Conventional LCA was specially designed for case-specific purposes. In other words, those methods are more likely to be used to conduct environmental impact assessment (EIA) for systems and products with little consideration of influential factors that vary in time and of variation in external conditions. For example, Wang et al. [69] so conducted LCA for a PV short-sea vessel engaged in the Bosphorus Strait, located in the Sea of Marmara that analysis results would be relevant to circumstances as defined and assumed in the study. In other words, this case-specific nature of the LCA study is still missing an underlying feature that needs to be considered to determine whether the same vessel may make a different performance under diverse scenarios and/or business cases, given that PV performances are highly dependent on the external conditions. In this regard, this past research can hardly answer whether the PV electric ships are ultimately optimal solutions or not.

The same issues were observed prevalent across most of the past LCA across industries; some representative examples are given in Table 2. That means the conventional LCA is neither effective to obtain a general trend nor understanding the relations of internal/external variables. This shortcoming also affects the LCA database which contains a large amount of data from certain scenarios/conditions that may be not relevant to other conditions. Moreover, conventional LCA coupled with such a database obtained from previous studies, cannot adapt to continuous changes in external conditions including time variation. Consequently, LCA investigations based only on existing data may not accurately reflect the dynamic features of the solar panels and electric propulsion, which will make great differences in ship performance.

Jang et al. [72, 73] have recently attempted to improve the LCA method by introducing the Parametric-Trend LCA which can compensate for these shortcomings to some extent. Nevertheless, this method is not highly relevant for implementing dynamic analysis because it also relies on the existing database.

Overall, conventional LCA methods/practices are unable to explore how an identical PV electric vessel might have significant differences in technical and environmental performance based on power production methods, service area, and regional climate conditions. To remedy the research gap, this paper was to introduce the Live-Life Cycle Assessment (LLCA) in the following section.

2. LLCA Method (vs LCA)

The LLCA was designed to be capable of responding to dynamic features of subjects through real-time data generation in aids of simulation and/or experiment. Rather than overly laden with the fixed dataset, the LLCA can offer a way that can investigate previously unexplored facts and confirm the overall effects of new technologies as well as quantitatively suggest the relations between variables such as different assumptions, inputs, scenarios, types of technologies, ship specifications, business cases, local/global conditions, etc. Figure 2 illustrates the key features of LLCA in comparison to the conventional LCA.

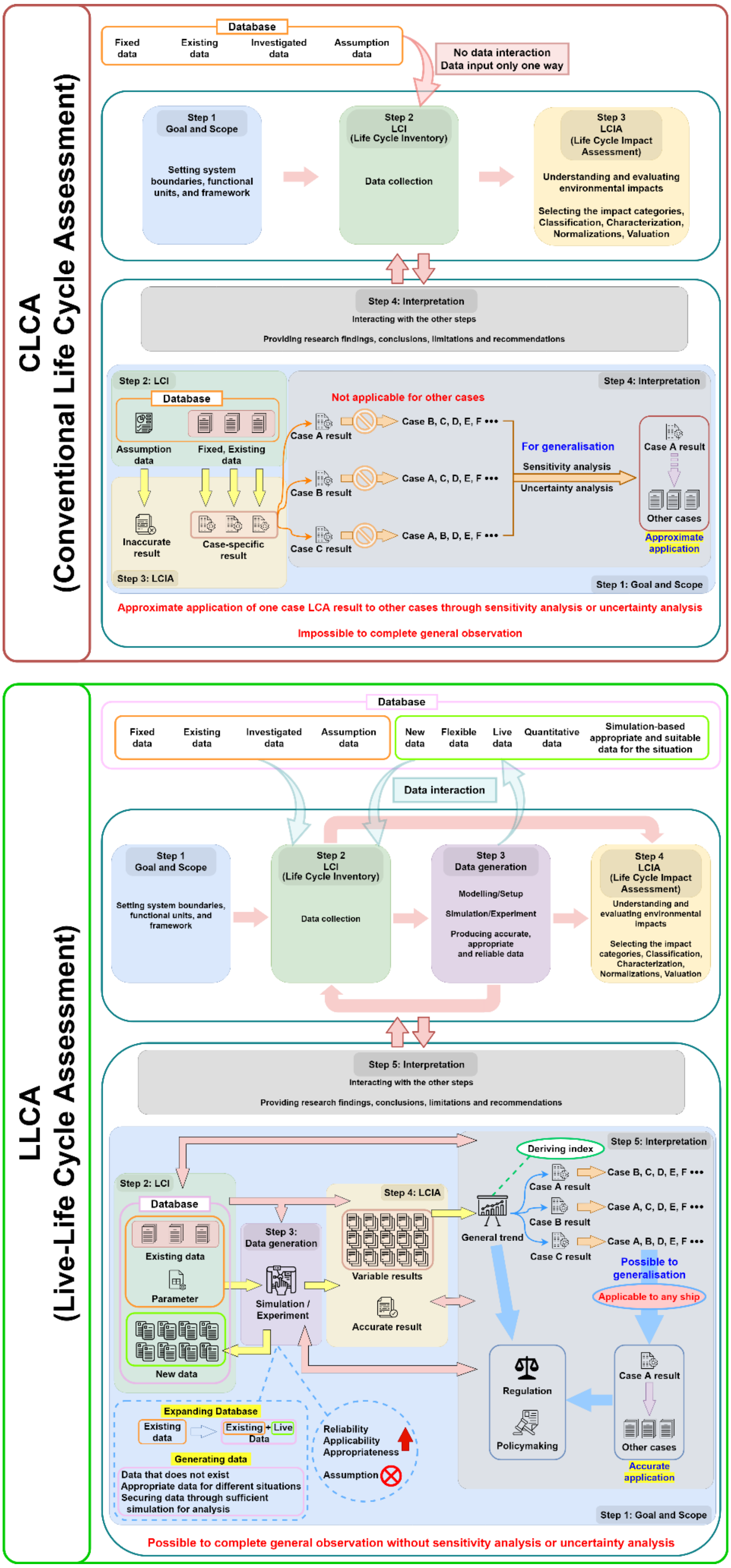


Figure 2. Live-Life Cycle Assessment framework and methodology compared to conventional LCA

As shown in Figure 2, the conventional LCA method simply consists of the following four steps according to the ISO guidelines: Step 1- Goal and Scope; Step 2- Lifecycle Inventory analysis (LCI); Step 3- Lifecycle impact assessment (LCIA); Step 4- Interpretation. On the other hand, Live-Life Cycle Assessment (LLCA) includes the new features of *“Step 3: Data generation*” where the Modelling/Setup & Simulation/Experiment step for input/output data generation. In addition to this, the rest of the existing LCA steps were also revised based on the purpose/functionality of LLCA.

Through the new step "Data generation", LLCA to be more reliable, universally applicable, and produce appropriate results. From this, the general trend can be known, the index of ships can be derived, and the research results can be directly generalised without the techniques used for generalisation in the conventional LCA, such as sensitivity analysis or uncertainty analysis. Therefore, based on more reliable data, it is possible to complete general observation, and the result of general observation can be immediately used for regulation and policymaking.

Figure 3 is a schematic representation of a case study conducted by applying LLCA. The necessity of LLCA application is proven through the case study, and the superiority of LLCA is verified by comparing the research results with the case of performing the same study using the conventional LCA.

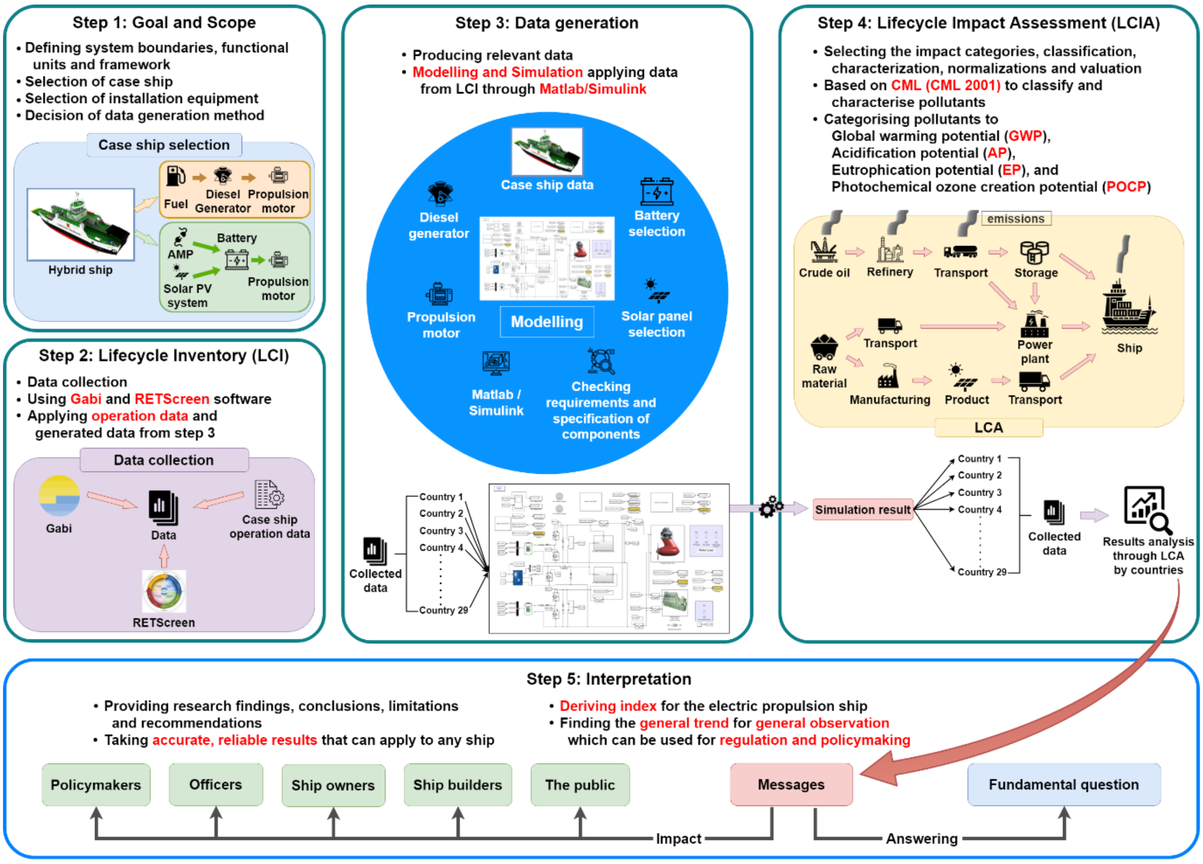


Figure 3. Schematic representation of a case study

2.1. Step 1: Goal and Scope

In this step, system boundaries, functional units and framework are defined and present based on ISO standards.

Conventional LCA studies have limited the boundary of goal and scope with a straightforward process from Step 1 to 4. However, the goal and scope of LLCA can establish a more scalable and extensive goal and scope, thanks to the data generation process. For the example of PV electric ships, the brevity of the solar PV system onboard may cause troubles with the irrelevance of data collection. On the other hand, LLCA can overcome such troubles by producing equivalent data sets through simulation and/or experiment which can iterate as many times/cases as proposed. Given this, LLCA will become more relevant and effective in studies where we need to obtain general understanding and observation on subject systems and ships under various different conditions.

This paper was proposed to find the answer to the fundamental question arisen in Section 1 to estimate the holistic environmental benefits/harms of PV electric ships under various operating scenarios illustrating the goal and scope of the case study that will be conducted through this paper.

A hybrid ship running on both diesel and plug-in battery was selected as a case ship. Then, the hybrid ship was assumed to be fitted with PV systems and the identical ships were assumed to have service engagement in 29 countries across the world. For comparative purpose, the operational conditions as the existing data were defined as ‘controlled parameters’ and the national electric grids and weather conditions were regarded as ‘experimental variables’ to determine the associations between the environmental performance of PV electric ships and the experimental variables. The solar PV and battery systems for the electric propulsion of the case ship was modelled under the Matlab/Simulink platform to estimate the power production/consumption during the voyage.

2.1.1. Electric propulsion ship

Based on the current practice of the case ship engaged in the West-Scotland coastal service [74], three credible operational scenarios will be investigated as below:

1) Diesel-electric operation (Case 1): electricity generated by diesel generators run propulsion motors.

2) Full battery mode (Case 2): the electric energy used by propulsion motors is supplied from the inland electricity grid.
3) Full battery with the solar PV system (Case 3): the electric energy used on the ship is only supplied by the batteries whose energy are supplied both from the inland electricity grid and the PV systems onboard.

2.1.2. Case ship selection

A hybrid RoPax ferry built by the Scottish shipyard of Ferguson Marine was selected as the case ship. Operational data and ship specifications were provided by the ship operator. The operational data was used for simulation model verification for battery operation. Solar panel systems were, then, modelled and fitted to the original hybrid systems in consideration of the size and space of the ship, allowing a more in-depth discussion on the eco-friendly ship. The onboard batteries are charged overnight via the shore connection.

Table 3. Information of the case ship

Case ship size and specification				
Length	39.99 m			
Beam	12.2 m			
Draught	1.73 m			
Deadweight	100 t			
Operation data of the case ship				
	Hours	Shaft power (kW)	Total load (kW) (including hotel load and losses)	Daily Total power consumption (kWh/day)
Transit mode (9 knots)	6.0	267.5	354	2124
Manoeuvring mode	0.6	120	152	91
Port mode	3.73	72	104	388
Total operation	10.33	-	-	2603
Overnight	13.67	-	-	-

2.2. Step 2: Life Cycle Inventory (LCI)

This step is to collect a variety of data appropriate and suitable to achieve the research goal and scope through the process of identifying, classifying, and quantifying all substances released into the environment, including pollutants, and all resources used in the production and operation of products. In other words, the success of Step 2 is also highly dependent on the quality of data and its accessibility. In other words, the data generation process in LLCA will enhance the Step 2 process as the results of simulations/experiments are directly converted into the input formats of Step 2 so that a number of LCI cases can be analyzed simultaneously.

Relevant data were collected from a variety of resources to estimate the technical and environmental performances of the case ship. The description of key data and sources is to follow as below:

2.2.1. GaBi

The functional units of environmental impact (GWP, AP, EP, POCP) on the production of national electricity in 29 countries adjacent to the sea were extracted from Gabi Database as shown in Figure 4. LCA is followed by simulations of the case ship sailing on power supplied by each country.

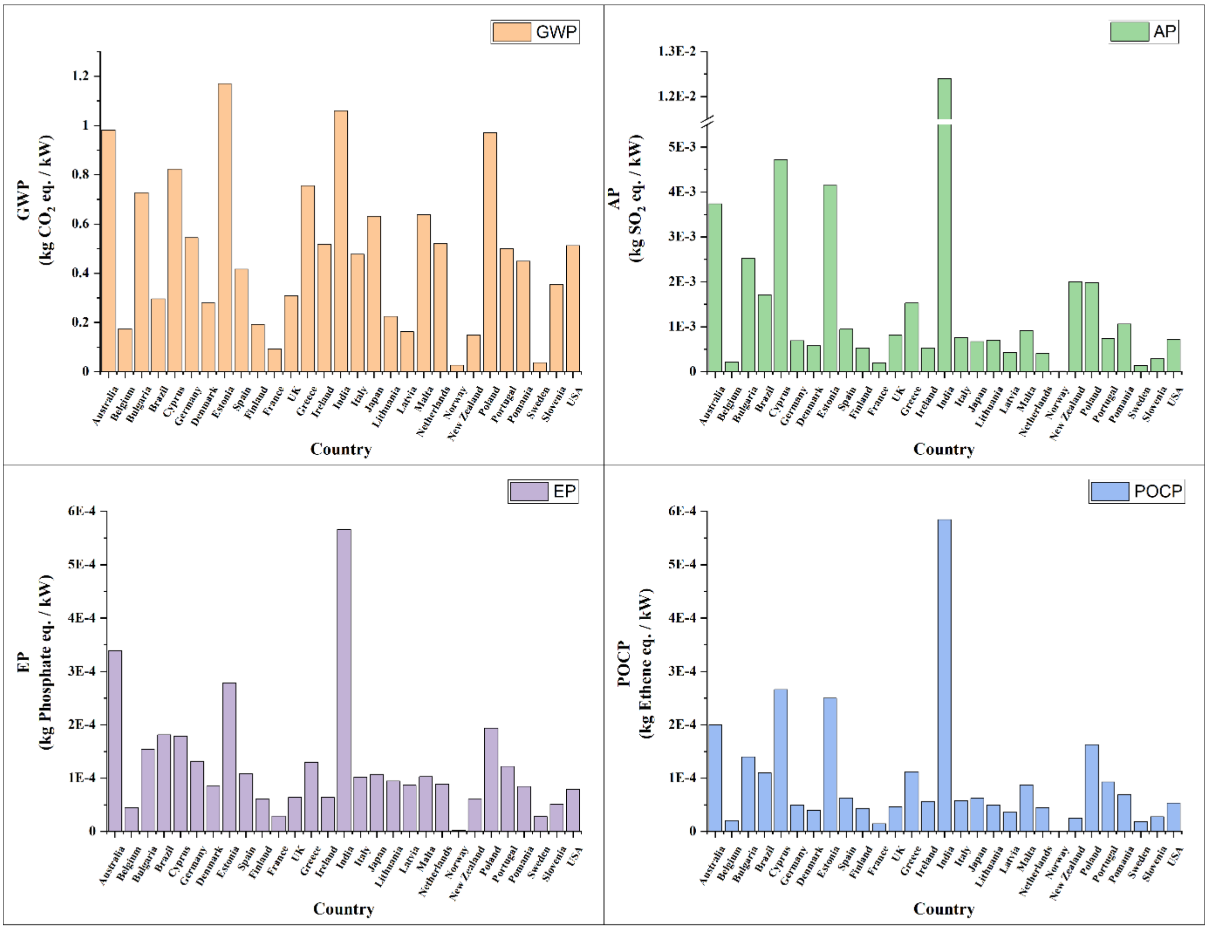


Figure 4. Environmental impact per 1kW of producing electricity in each country

2.2.2. RETScreen

For simulation of the Solar PV system onboard, weather data for the 29 countries were collected through RETScreen software as shown in Figure 5. By inputting the monthly average of solar irradiance and temperature data for location into the modelling, the difference in electric production level across the nation was estimated through simulation as shown in Figure 6.

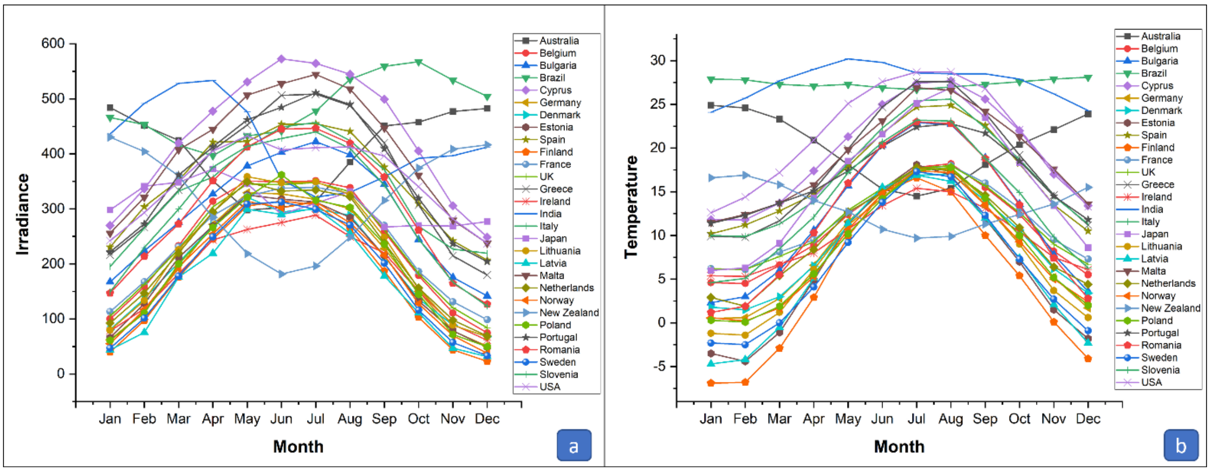
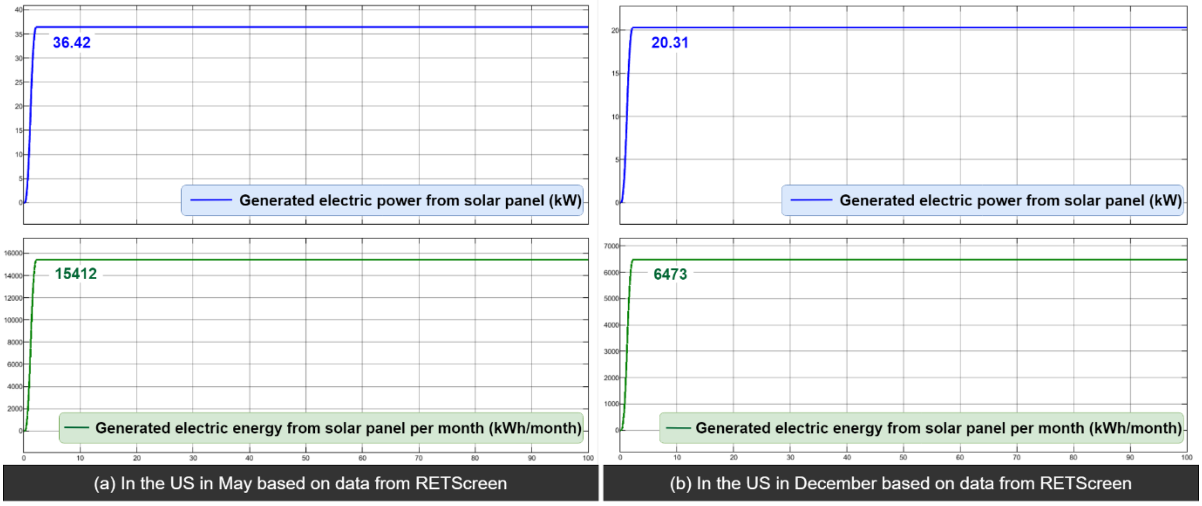


Figure 5. Graphs monthly irradiance and temperature for the 29 countries



(a) In the US in May based on data from RETScreen

(b) In the US in December based on data from RETScreen

Figure 6. Different electric production levels from installed solar panels across environmental factors, (a) in the US in May, (b) in the US in December

2.3. Step 3: Data generation

As the key feature of the Live-Life Cycle Assessment, this Step 3 was designed to produce relevant data which has not yet been obtained in the actual industrial field nor stored in the LCA database. This data generation process will enable us to be free from the inherent issues of data availability/reliability; conventional LCA overly rely on the existing data from previous studies in many cases, LCA researchers are struggling with the lack/irrelevance of data. On the other hand, through numerous iterations of the Data generation process, LLCA can enhance the analysis to more intuitively and quantitatively present various LCA results, providing correct guidelines for policy, industry, and the public. These results will ultimately improve the overall quality of the LCA research, providing better environmental understanding and parametric sensitivities on the ship performance of ships.

2.3.1. Electricity distribution system

In the past, the AC power distribution system was widely adopted for most electric propulsion ships. However, with the convenience of switching power thanks to advanced development on power electronics technology, DC distribution systems have prevailed as the mainstream of electric propulsion ships [19, 20, 39]. The advantages of the DC distribution system over the AC distribution system in the electric propulsion ship can be summarised as below [19, 39, 75].

1) Unlike AC based propulsion ships that require generators to be operated at a fixed speed regardless of the output to maintain the rated frequency, DC based propulsion ships can change speed freely, which improve the propulsion efficiency at low loads. In general, generators used in the DC system were reported to reduce fuel consumption by 20% or more at low load as shown in Figure 7 [20].

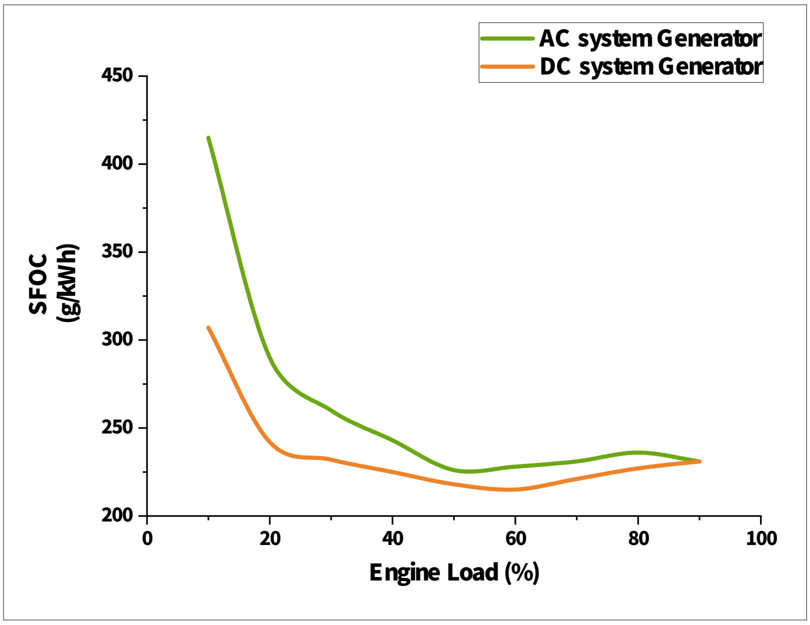


Figure 7. SFOC of generator in different current systems

2) Fast parallel operation is possible because generator synchronization is not required.
3) Installation weight and volume can be reduced by simplifying or exempting components such as the main AC switchboards, converter transformers and harmonic mitigation equipment, thereby reducing the propulsion loads and reducing fuel consumption.
4) Reduced maintenance costs due to fewer breakdowns since the engine continues to operate at its optimum operating point.
5) Energy storage system (ESS) can be freely connected, and additional energy sources such as solar panels, fuel cells, and supercapacitors can be installed to save energy and obtain benefits such as peak shaving and load levelling.
6) Unlike AC systems where reactive power is present, DC systems have no problem with reactive power interactions, making it easy to maintain power stability.

Reflecting these benefits and current industry trends, the case ship was modelled on the basis of a DC system.

2.3.2. Propulsion system

The predominantly used propulsion system is a mechanical type that uses fuel oil directly into the main diesel engine to obtain propulsion power through rotation of the internal combustion engine. The electric propulsion system, on the other hand, is a system in which electric energy is obtained by operating generator engines, batteries or other energy sources to run the propulsion motor. Of the two types, the electric propulsion system is known to prevail over the mechanical propulsion system both economically and environmentally especially for short-route ships [31, 76]. Figure 8 briefly shows the difference in system configuration as well as lifecycle energy supply stages between the two systems.

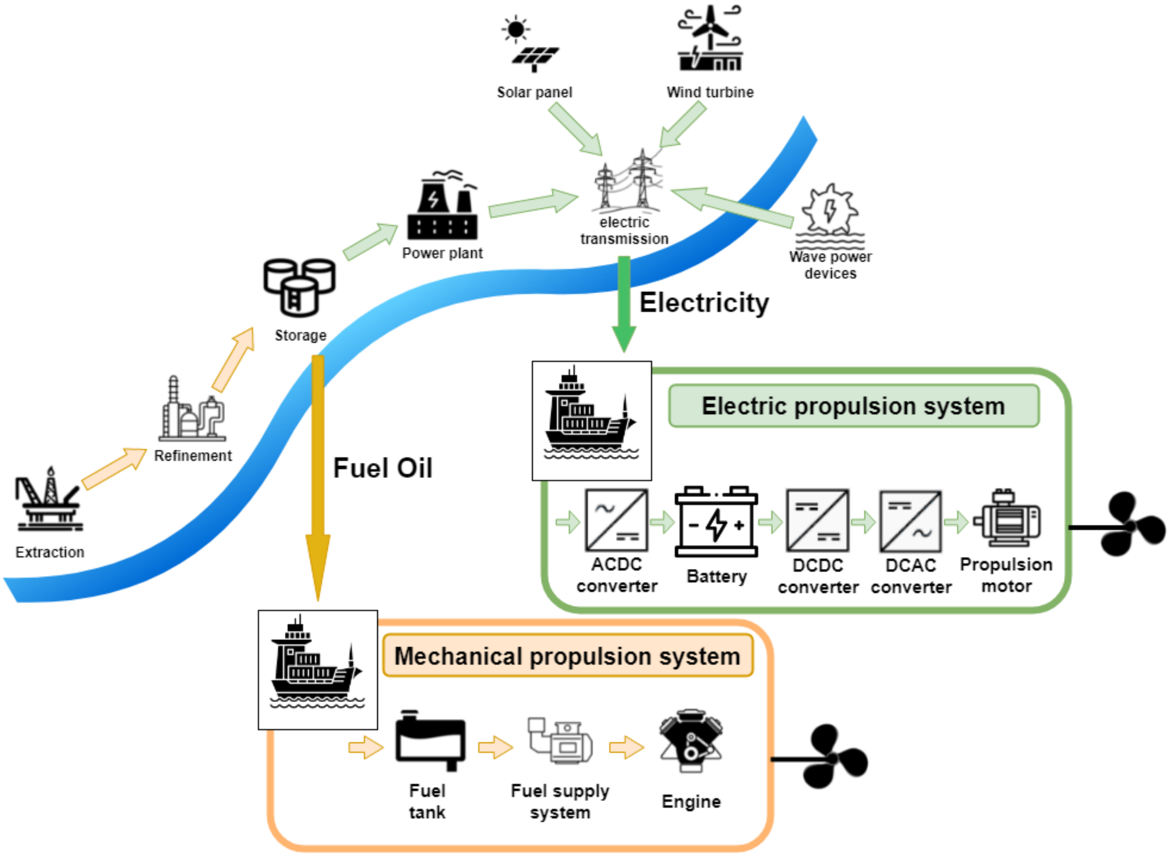


Figure 8. Propulsion systems

2.3.3. Modelling

Based on the concept of electric propulsion ship as shown in Figure 9, the modelling is completed by using Matlab/Simulink by comprehensively considering the following parts.

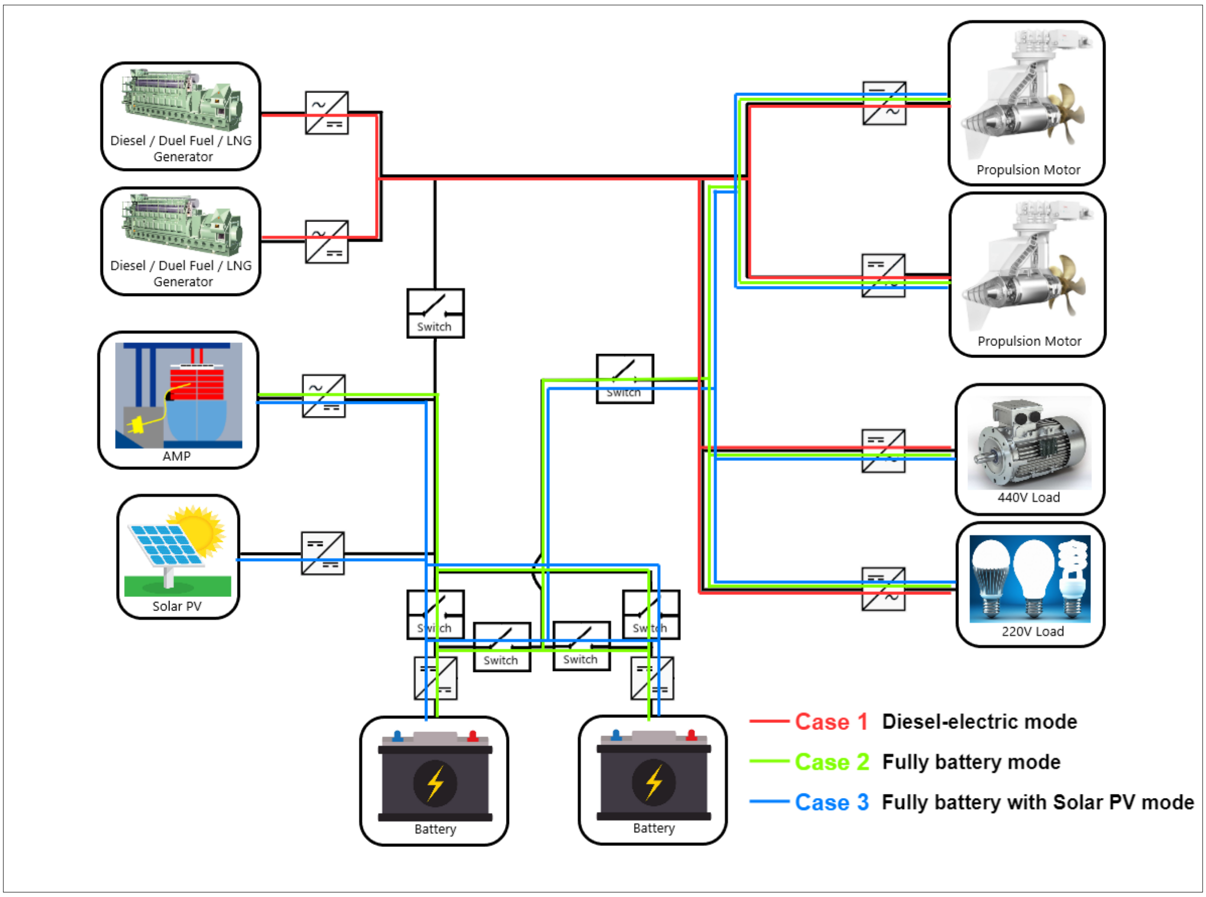


Figure 9. Conceptual design of the case ship

Table 4. Specification of applied Propulsion motor, Diesel generator, Battery, and Solar panel

Specification of Propulsion motor	
Rated Power	375 kW
Speed	600 RPM
Weight	2210 kg
Efficiency	97 %
Power Factor	0.96
Cooling system	Water-cooled
Specification of Diesel generator	

Engine maker	Volvo Penta
Engine designation	D13-MG
Engine type	4-stroke, direct-injected
Bore/stroke	131 mm
Compression ratio	18.5 : 1
Engine speed	1800 rpm
kWm	400
kWe	380
kVA	475
SFOC at 50 load	212 g/kWh
SFOC at 75 load	212 g/kWh
SFOC at 100 load	209 g/kWh
Specification of Battery	
Energy	8.8 kWh
Nominal Voltage	88 VDC
Capacity	100 Ah
Dimensions	L 580 mm, H 380 mm, W 320 mm
Weight	90 kg
Efficiency	> 98 %
Solar panel specification	
Maker	Sunpower
Model	SPR-X21-345
Maximum Power	345 W
Open circuit Voltage (V_{OC})	68.2 V
Short circuit current (I_{SC})	6.39 A
Maximum Power Point (MPP) Voltage (V_{MPP})	57.3 V
Maximum Power Point current (I_{MPP})	6.02 A
Module Efficiency	21.5 %
Total installation of Solar PV system	
Total number of units	245
Array	5 series × 49 parallel
Voltage at MPP	286.5 V
Power capacity	84.525 kW

1) Case 1: Diesel-electric mode

This system uses diesel generators to produce electricity to propel by supplying that to the propulsion motor. The same propulsion motor is used in all cases covered in this paper, and the same specifications as the original motor mounted onboard are applied to modelling.

A 400 kW diesel generator made by Volvo Penta was modelled and the specific fuel oil consumption (SFOC) of the generator over various loads were used to calculate fuel consumption under the identical operation as the original operational profile.

2) Case 2: Full battery mode

In this mode, the electricity is supplied from onshore alternative marine power (AMP) rather than using onboard generators, and it is used to charge the onboard batteries to power the propulsion motors.

The efficient and safe operation should be secured by selecting the most suitable energy storage devices for the ship propulsion purpose among the various types shown in Figure 10 [77] which clearly indicates that batteries are an excellent energy storage type when considering both power density and energy density, so it is largely used in a wide variety of industries including marine vessels [31, 78]. In particular, Li-ion batteries are found excellent in power density [79-81]. As a result, the case ship was modelled with Li-ion batteries for the onboard power system.

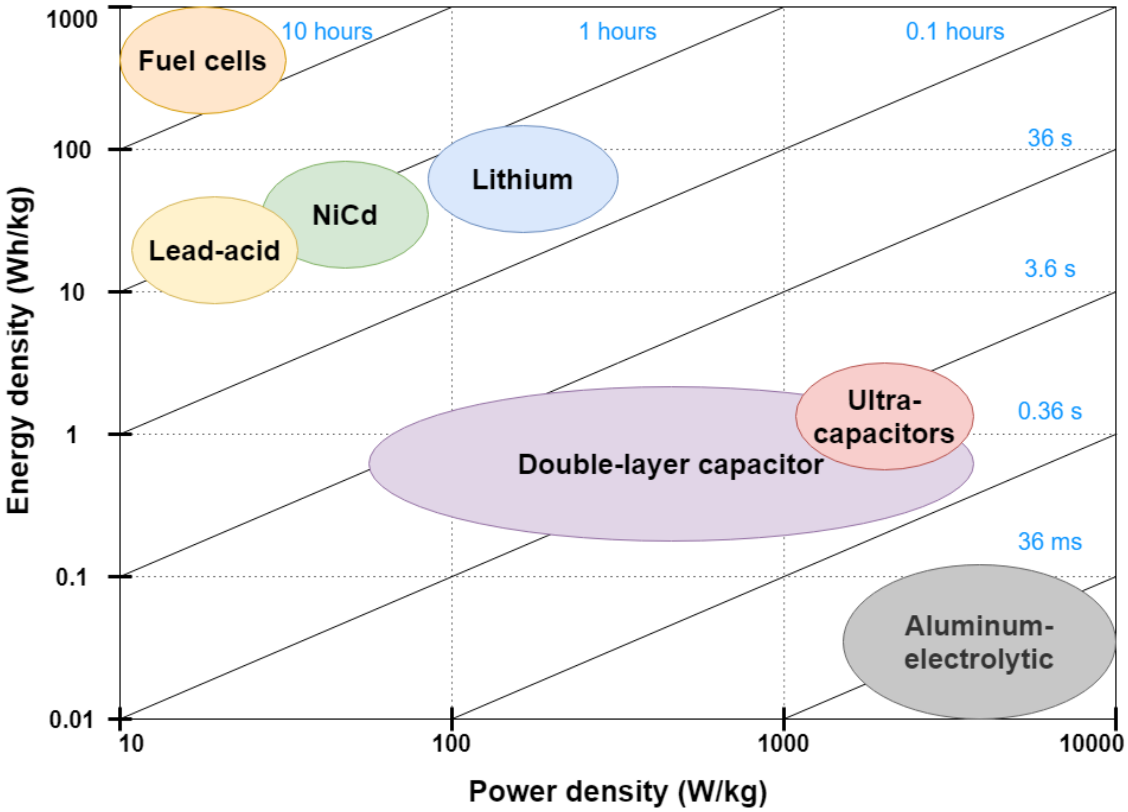


Figure 10. Power density and Energy density of energy storages [79]

Figure 11 [82] compares the capacity retention of batteries over the number of operation cycles. It reveals that batteries can be used for a longer period if kept between 25 and 75% of the battery state of charge (SOC). Considering battery lifetime and cost, installation space and weight, etc., charging at 25% and discharging at 75% can be the best battery management decision.

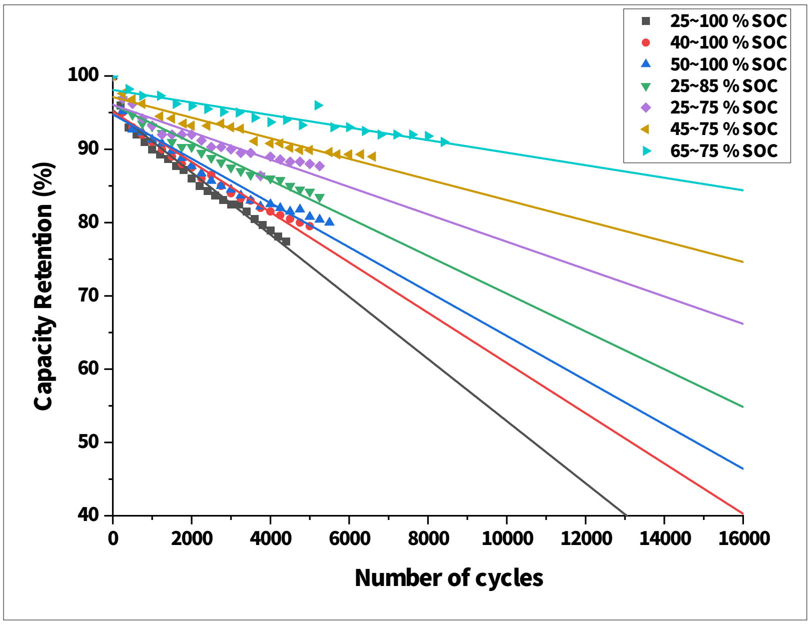


Figure 11. Actual capacity loss of battery by charging and discharging and expectation of battery life by extrapolation

For full battery mode, to ensure sufficient energy storage on batteries, onboard power consumption analysis was conducted using the operation data of the case ship. In response, daily energy consumption was estimated at 2,603 kWh. As the battery is used between 25% and 75% SOC, only 50% of the total battery capacity is in service. Since the battery was not planned to be charged during service, therefore, a total of 5,206 kWh was estimated to be fitted onboard for full battery mode. Energy 88 produced by PBES, a type of lithium battery, was selected for modelling.

It has 8.8 kWh per battery and 296 batteries are fitted to a single pack, resulting in 2,604.8 kWh per pack. For safe and reliable battery operation, two packs of batteries were adopted for the case ship. Considering the power transmission line and space of battery storage, the battery arrangement for the pack is four series and 74 parallel, so that one battery pack has 352 Volt, 7400 Ah, 2604.8 kWh, and L 2.32 × W 2.56 × H 3.8 meters.

3) Case 3: Full battery with Solar PV mode

The operation method is the same as that of the full battery system, but in the process of supplying electricity, the main source is to be the solar PV system and supplemented by AMP.

Considering the space available for the case ship, a total of 245 PV panels can be installed with the optimal production of 84.525 kW at 1000 W/m^2 and 25 .

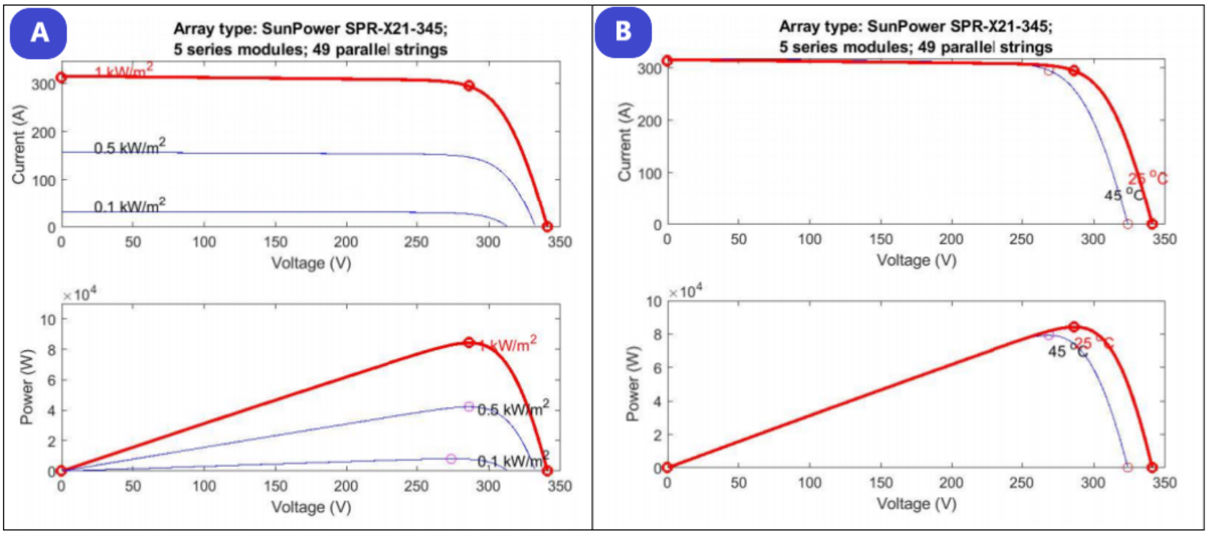


Figure 12. Maximum Current and Power graphs according to the voltage produced by installed solar panels; (A) Graphs according to irradiance at 25 ℃, (B) Graphs according to the temperature at 1000 W/m^2 irradiance

The critical drawback of the solar PV system is that the amount of energy produced varies significantly depending on whether conditions [30, 31]. Therefore, to improve power quality and reliability, the electric power produced by the solar PV systems was proposed to be stored in the onboard battery, and the constant power from the battery would be supplied to the propulsion motors. Since it has two battery packs, it is designed so that when one battery pack is charged from the PV systems, the other one is discharged to the propulsion motors.

Considering all parts explained above, modelling was completed by using Matlab/Simulink as shown in Figure 13.

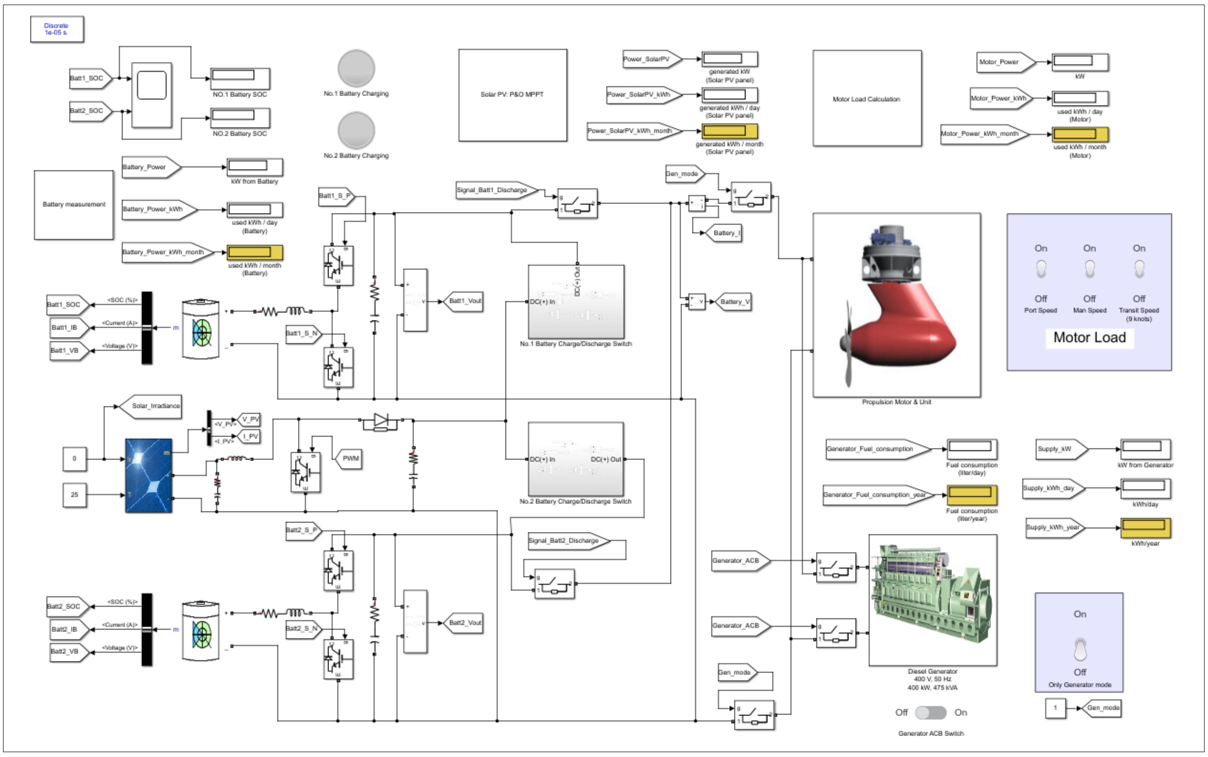


Figure 13. Modelling by using Matlab/Simulink

2.3.4. Simulation for each case

Each case discussed in the previous section can be presented in the simulation model as shown in Figure 9.

In Case 1, marine gas oil (MGO) was selected for diesel engine fuels in consideration of maritime emission regulations. Since emissions from the production and the supply of MGO vary from country to country, the final emissions are calculated taking into account data from eight countries to fuel refinement, provided by Hwang et al [67]. Results of Case 1 were used as baselines to quantify the environmental benefits/harms of Cases 2 and 3.

Simulations were carried out and one example is shown in Figure 14 that the case ship operates on the coast of the US in December. Then based on the results of it and the data of diesel generators, fuel consumption was calculated.

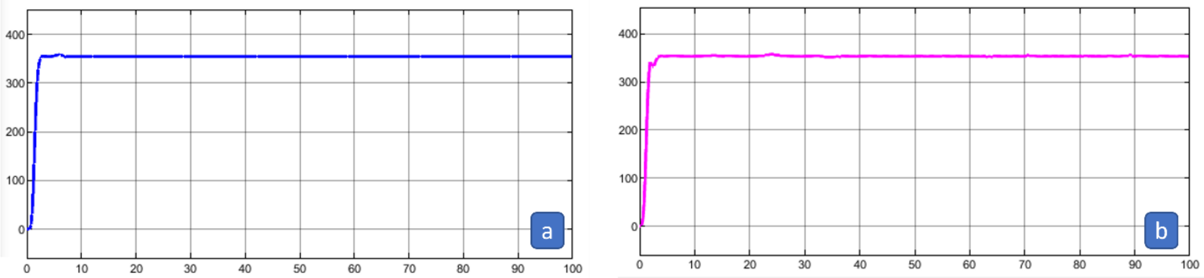


Figure 14. Simulation results from example of Case 1: (a) Power consumed by propulsion motor (kW), (b) Power generated by diesel generator (kW)

In Case 2, the ship runs on the electric energy stored in the onboard batteries and the daily power consumption was estimated, so was the amount of power supplied from AMP. Environmental impact assessment is based on the fact that different countries generate different emission levels for the same amount of electricity supplied to the case ship due to the differences in the ways electrical energy is produced.

One of the simulation results is shown in Figure 15 that the case ship operates on the coast of the US in December. The simulation proceeds assuming that both No. 1 & 2 battery packs are charged at 75% SOC through AMP. Currently, power is supplied to the propulsion motor from the No. 1 battery and the No. 2 battery is in charging mode as a standby without charging/discharging. When the No.1 battery SOC reaches 25%, the mode is changed and the power supply starts from the No.2 battery.

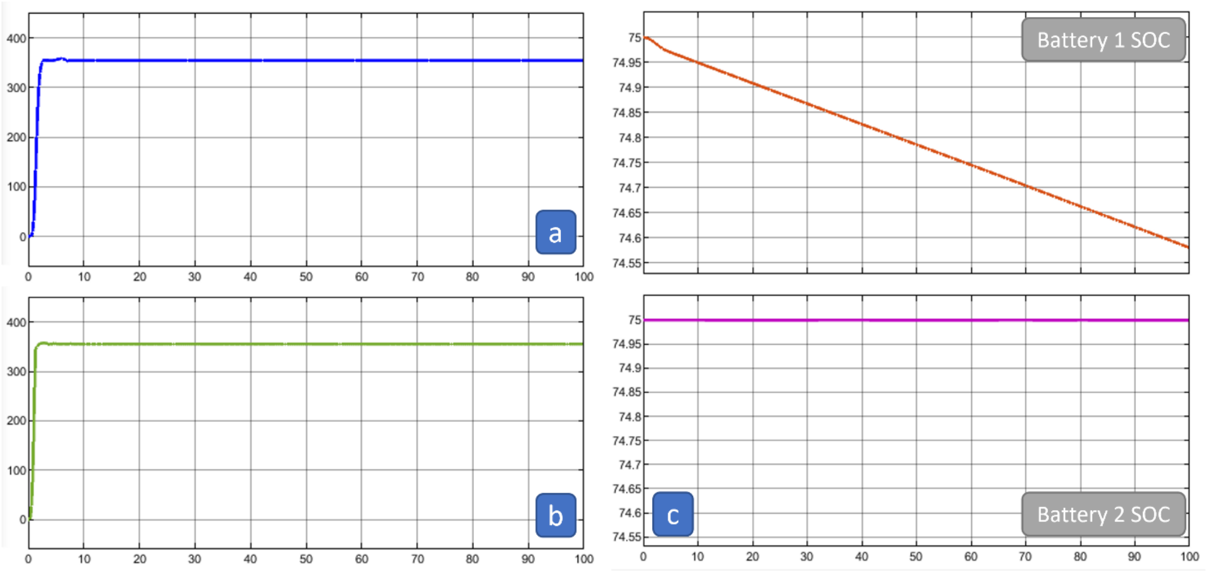


Figure 15. Simulation results from example of Case 2: (a) Power consumed by propulsion motor (kW), (b) Power supplied by battery (kW), (c) Battery SOC (Battery 1- Discharge mode, Battery 2- Charge mode)

In Case 3, the amount of the electricity supplied from AMP can be reduced by adding the electricity production from the solar PV systems additionally fitted to Case 2. The advantages of the PV systems would be discussed in comparison to Case 2.

The simulation result shown in Figure 16 is the same as the case 2 simulation result. However, solar panels are installed on the case ship, and the electric energy produced through the solar panels is stored in the No.2 battery, which is the charging mode, accordingly.

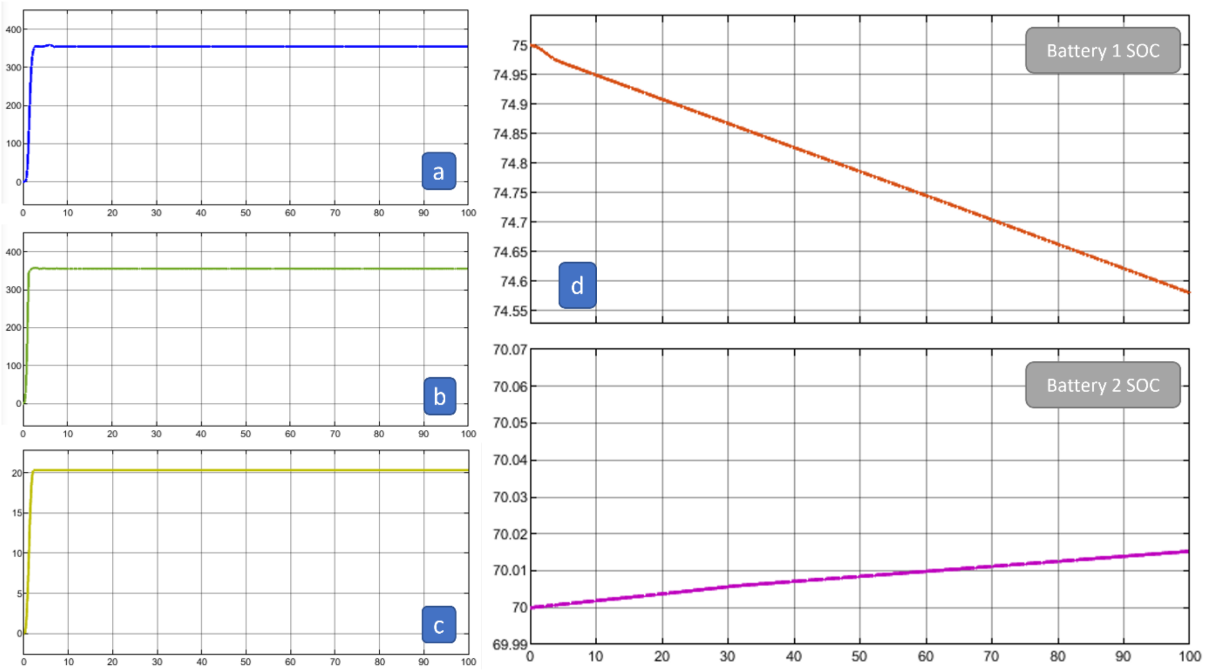


Figure 16. Simulation results from example of Case 3: (a) Power consumed by propulsion motor (kW), (b) Power supplied by battery (kW), (c) Power generated by solar panels (kW), (d) Battery SOC (Battery 1- Discharge mode, Battery 2- Charge mode)

2.4. Step 4: Life Cycle Impact Assessment (LCIA)

Corresponding to Step 3 in the conventional LCA process, this LCA step is to evaluate potential environmental impacts by transforming the obtained LCI results into representative impact indicators (potentials). The LCIA includes the following steps: Selecting the impact categories, Classification, Characterization, Normalizations, Valuation. In the LLCA this process can be re-named as “comparative assessment” since the effect of obtaining extensive data and analysis results under various scenarios can be interpreted as the generalization process where we can compare each scenario, thereby confirming the key parameters and correlations which contribute to the environmental impacts of systems and ships.

Generally, existing ships are built based on the mechanical propulsion system consuming fossil fuel causing emitting CO, CO2, CH4, N2O, SOX, NOX, PM and NMVOC [10]. Among several impact assessment methods to classify and characterise, CML (CML 2001) method is used in this paper. Based on this method, those pollutants can be categorised as global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and photochemical ozone creation potential (POCP) as shown in Figure 17. LCA is conducted by comparing the case applied with and without solar systems, and the benefits of utilizing the electric propulsion ship applied with renewable sources are discussed through those results.

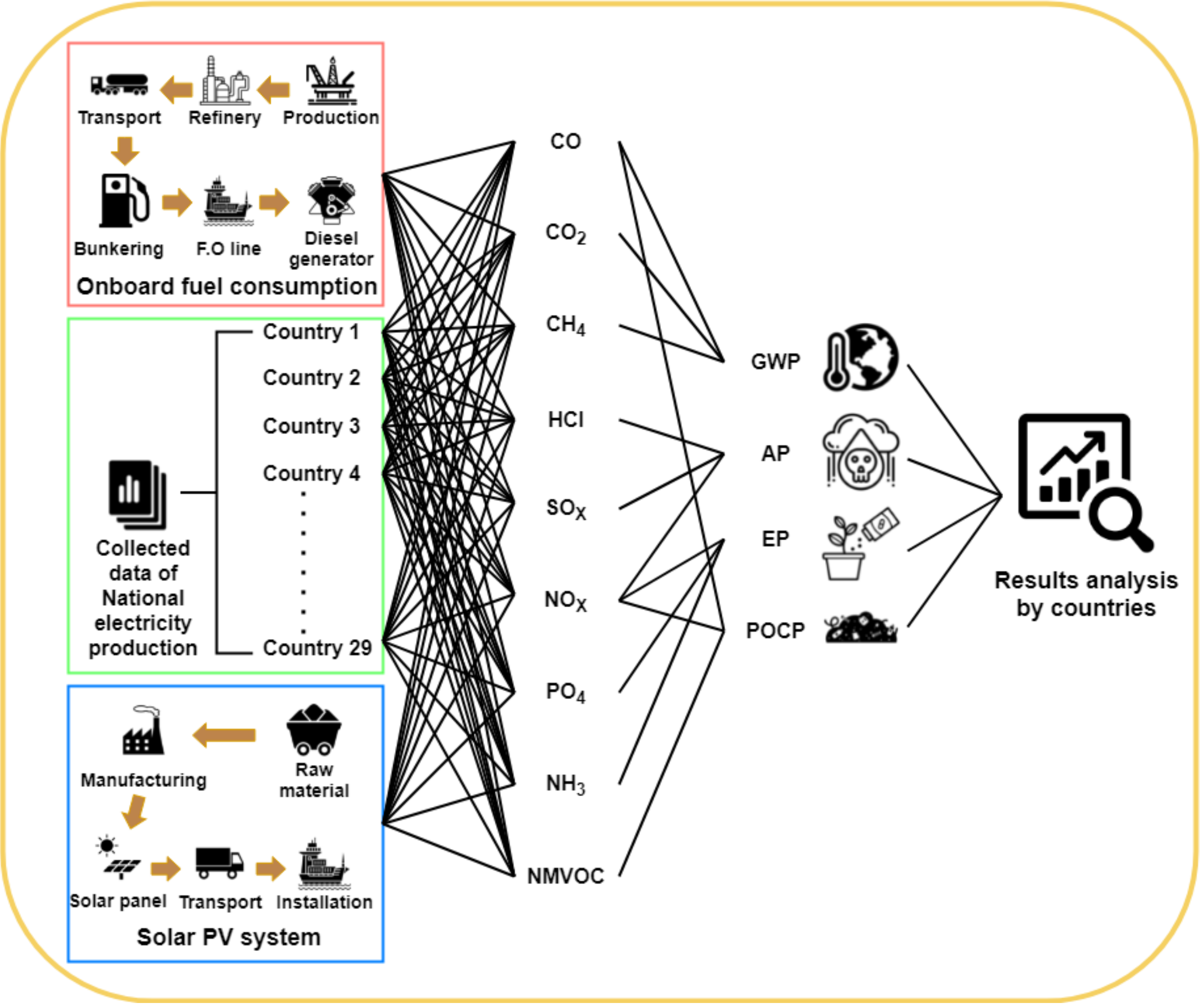


Figure 17. LCA procedure

2.5. Step 5: Interpretation

As the last stage of LCA research, it continuously interacts with the other steps to identify potential issues with goals and scope, and the information classified and characterised in LCI and LCIA is verified and evaluated. It also provides an understandable and comprehensive source of research findings and recommendations that can be utilised by decision-makers in relation to the initial primary objectives of the study. This step includes the following key points: Identification of specific issues based on LCI and LCIA steps; Evaluation taking into account parameters, consistency and completeness; Providing conclusions, limitations and recommendations.

Again, the excellence of LLCA can be placed on this step where we can observe a number of interesting points through the process of comparative assessment across all credible scenarios. Through a much higher level of verification and interpretation, the LLCA can offer meaningful insights / recommendations to policymakers and the public.

In summary, the main difference between traditional LCA and LLCA can be summarised as follows. Conventional LCA has been looking for a handful messages from a single case study, but these findings tell nothing to other cases. On the other hand, the LLCA finds comprehensive messages in thousands or more studies, and these findings have direct implications in other cases. The excellence of the LLCA will be demonstrated through the case study in the section to follow.

3. Analysis results (Steps 4 and 5)

3.1.1. Case 1: Diesel-electric mode

Simulation results of Case 1, where the ship would only run on diesel generators using conventional fuel, show that the power consumption was estimated at 950,139 kWh per year. 199,493 kg of diesel (named as marine gas oil or MGO) per year would be consumed for the corresponding power. The numerical values were fed into the LCA for the MGO production (upstream) and the onboard usage (downstream) for eight different countries in aids of LCA software, called GaBi, and its database. In addition, the following functional units provided by Hwang et al. [67] were applied for LCIA.

Table 5. Functional units of MGO usage per kg

GWP (kg CO_2 eq.)	AP (kg SO_2 eq.)	EP (kg Phosphate eq.)	POCP (kg Ethene eq.)
3.2564	0.0453	0.0341	0.0910

LCIA results can be summarized in Figure 18. In general, the use of MGO produced in India was found to have the greatest environmental impact and the United States was also identified as an influential emission producer within the categories examined. It clearly indicates that the same ship can make a different environmental performance according to service areas. The maximum gap of annual emission levels was found between India and the UK. When the case ship operates in India, it will emit 40,697 kg CO_2 eq., 547 kg SO_2 eq., 23 kg Phosphate eq., 45 kg Ethene eq. more than it operates in the UK.

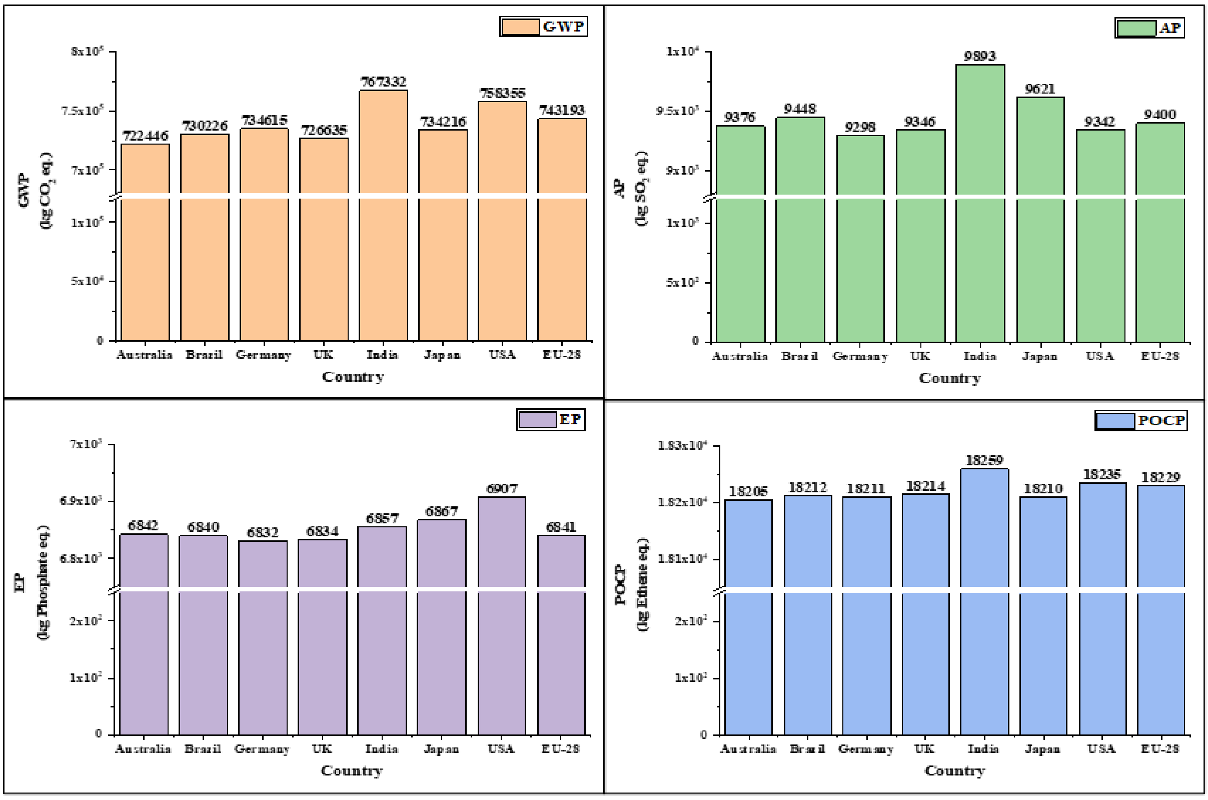


Figure 18. Results of case 1 by GWP, AP, EP and POCP

3.1.2. Case 2: Full battery mode vs Case 3: Full battery with Solar PV mode

In Case 2 where the case ship runs on full battery mode whose electricity is charged from onshore electricity grids, the LCA studies were conducted for 29 countries in consideration of their national electricity production footprints in aids of GaBi database. MATLAB Simulation estimated 951,864 kWh of annual electricity consumption from the battery.

On the other hand, Case 2 was compared with Case 3 where the PV system would be applied to the same vessel so that the electricity demand onboard would be partially covered by the solar energy. To estimate the electricity production during the voyage, the 29 countries' geographical conditions were investigated and used as input for MATLAB simulation.

Figure 19 shows the differences in the electric load shares between the AMP and the PV systems. The gaps across the countries are caused by the different weather conditions; some are in favour of PV systems and some others are not.

To be specific, it appears that the case ship would have the maximum benefit of solar energy if it is engaged in Brazil coastal service, indicating that 18.73 % of total energy consumption (equivalent to 178,298 kWh), could be supplied by the onboard PV systems. It is followed by Cyprus (168,187 kWh, 17.67 %), Malta (158,190 kWh, 16.62 %), Australia (154,850 kWh, 16.27 %) and India (153,980 kWh, 16.18 %). In contrast, the service on the coast of Latvia was found with the least level of benefits obtainable from the PV systems; only 8.06 % which is 76,753 kWh. Similar trends were found with Ireland and Sweden at 8.29 % (78,918 kWh) and 8.76 % (83,366 kWh), respectively.

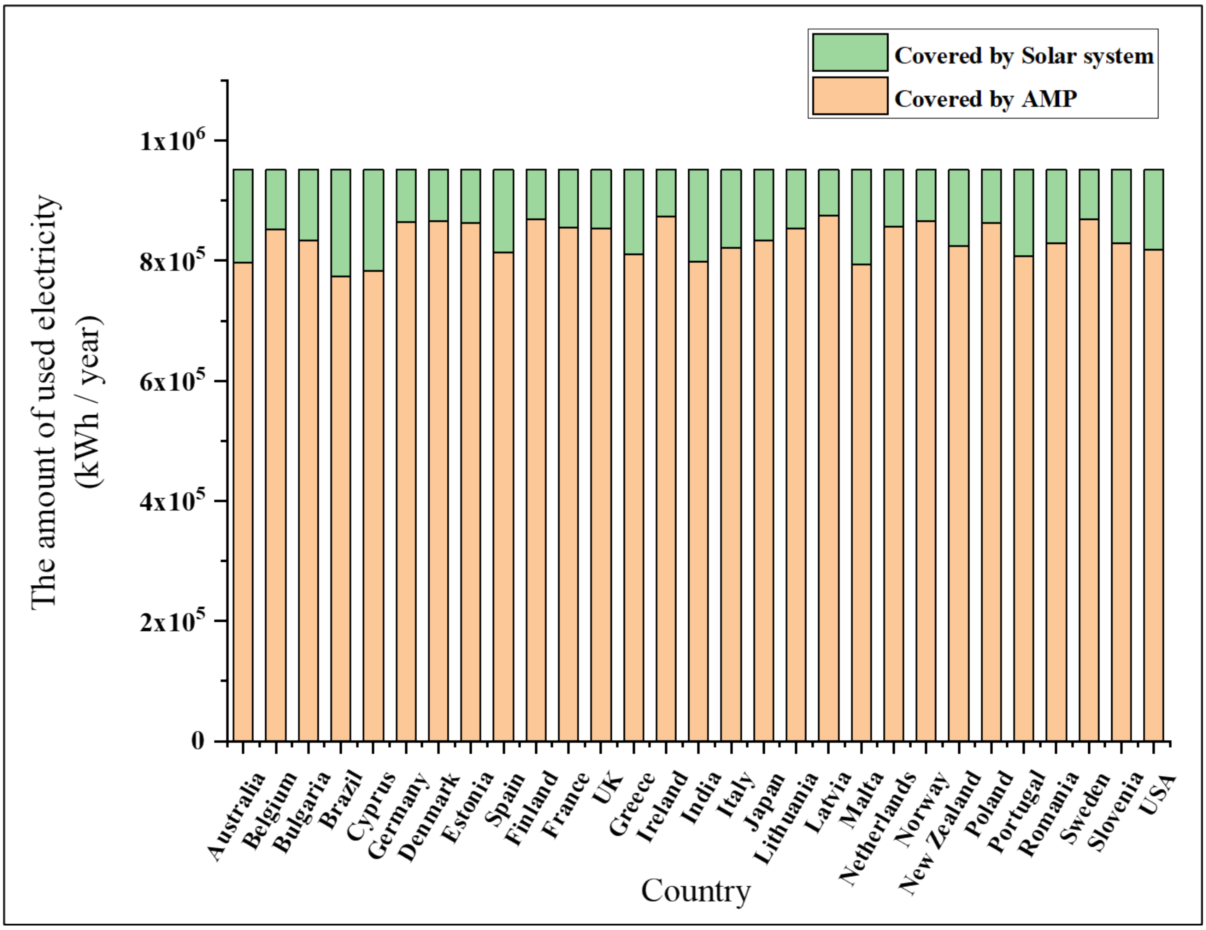


Figure 19. Case ship's electric power supply method by country

Analysis results clearly demonstrate the weather conditions of each country are a key parameter that determines the performance of solar PV systems, daunting the use of PV systems for ships sailing in cloudy and cold regions. Again, simulation results were applied for the LCA as input parameters coupled with external data on the environmental impacts of hybrid-powered ships studied by Jeong et al [58]. Table 6 shows the functional units of solar PV system; unit environmental impact per 1 kWh electricity production from solar PV systems.

Table 6. Functional units of Solar panel per kW

GWP (kg CO_2 eq.)	AP (kg SO_2 eq.)	EP (kg Phosphate eq.)	POCP (kg Ethene eq.)
0.0671	2.82⯑10^{-4}	2.11⯑10^{-5}	2.45⯑10^{-5}

LCIA results for Cases 2 and 3 across the 29 countries are shown in Figure 21 and Figure 22. Given 951,864 kWh of annual electricity consumption of the case ship, in terms of GWP, Estonia was identified as the country with the most emissions by emitting about 1,113,680.9 kg CO_2 eq., followed by India, Australia and Poland. However, when the Solar PV system was applied, Australia could have a better result than Poland as shown in Figure 21 and Figure 22. As Table 7 shows, coal makes a greater contribution to GWP, compared to other energy sources. This trend can be clearly seen in Figure 20. The countries with high GWP values are evident of the high reliance on coal-based power generations [83]. Conversely, hydroelectric power generation has the lowest value for all pollutant emissions, including GWP. Nuclear generation also shows a similar trend as indicating relatively lower emissions. For example, Norway and Sweden where highly rely on hydroelectric and/or nuclear power generation, reveal the lowest levels of environmental impacts across the countries.

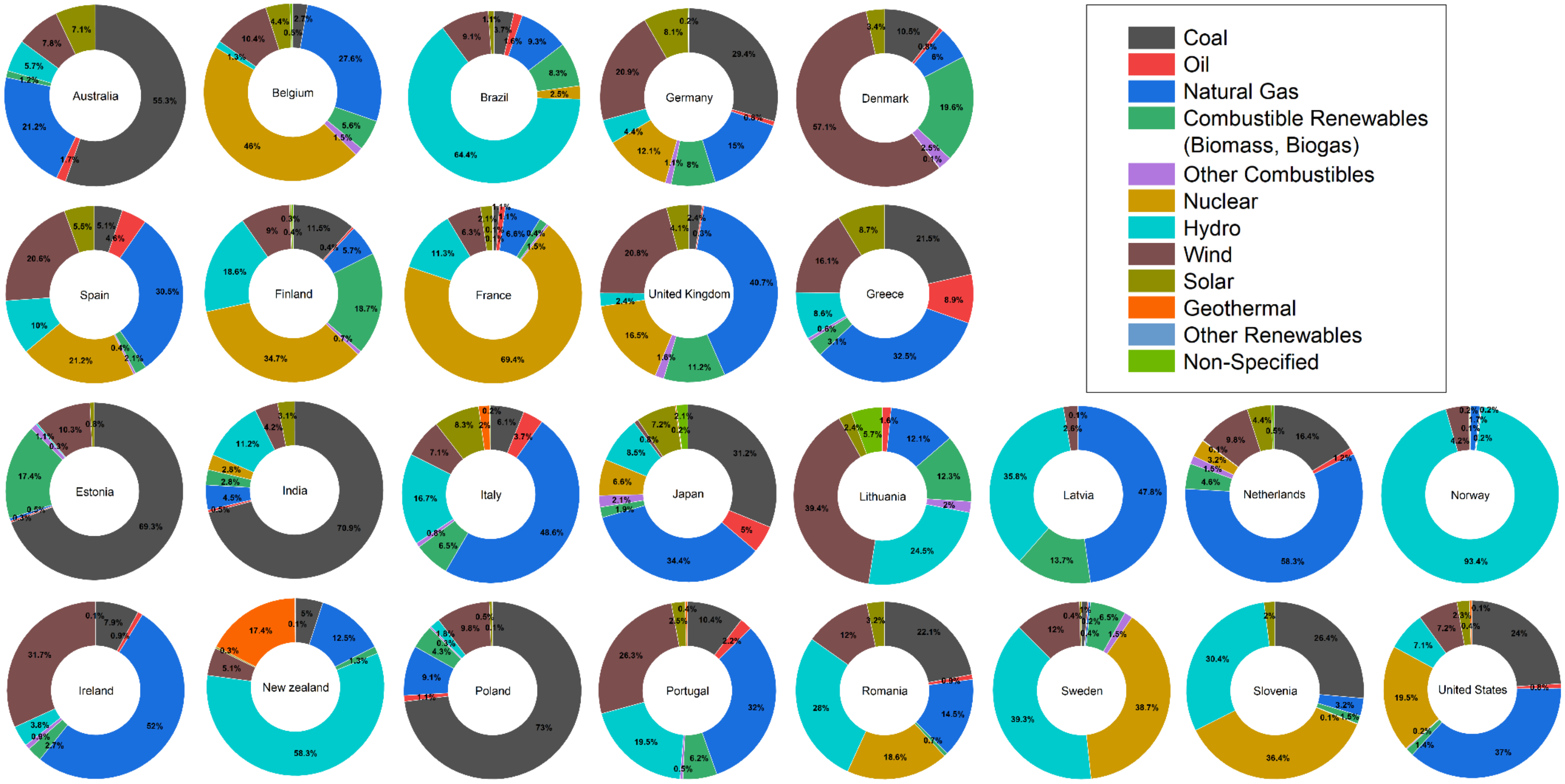


Figure 20. The proportion of resources used to generate national electricity in each country [83]

Table 7. Emission factors of energy sources for generating electricity [58]

	GWP (kg CO_2 eq.)	AP (kg SO_2 eq.)	EP (kg Phosphate eq.)	POCP (kg Ethene eq.)
Coal	9.12×10^{-1}	1.20×10^{-3}	1.46×10^{-4}	9.09×10^{-5}
Oil	7.06×10^{-1}	2.52×10^{-3}	1.36×10^{-4}	1.45×10^{-4}
Natural Gas	5.65×10^{-1}	6.01×10^{-4}	9.67×10^{-5}	6.79×10^{-5}
Nuclear	5.68×10^{-3}	3.13×10^{-5}	6.13×10^{-6}	2.62×10^{-6}
Hydro	6.24×10^{-3}	6.90×10^{-6}	9.03×10^{-7}	3.80×10^{-7}
Wind	1.05×10^{-2}	2.92×10^{-5}	3.18×10^{-6}	1.04×10^{-6}

For local pollutants of AP, EP and POCP, India's emission levels were shown overwhelmingly high. It clearly shows that the same electric propulsion ship sailing the coast of Norway and receiving electricity from Norway's national power grid will perform absolutely different environmental outputs if dispatched to the coast of India. This finding conveys an important message that electric propulsion ships themselves are not to be classified as 'green ships'. Instead, after evaluating actual performance across various geographical conditions and electricity grids, we can finally confirm whether they are truly green or not.

In addition, the application of PV systems was proven significantly effective in reducing environmental impacts across most nations. It is because the lifecycle emissions from the PV systems were found much smaller than those from power plants, except for hydropower and nuclear power, to produce an equal amount of electricity as shown in Table 6 and Table 7. Paradoxically, in Norway and Sweden, where the proportion of hydro and nuclear power generation is higher than other methods, solar power systems have slightly higher emissions when applied to ships.

It is also worth noting that the comparison of Cases 2 and 3 results with the diesel operation (Case 1).

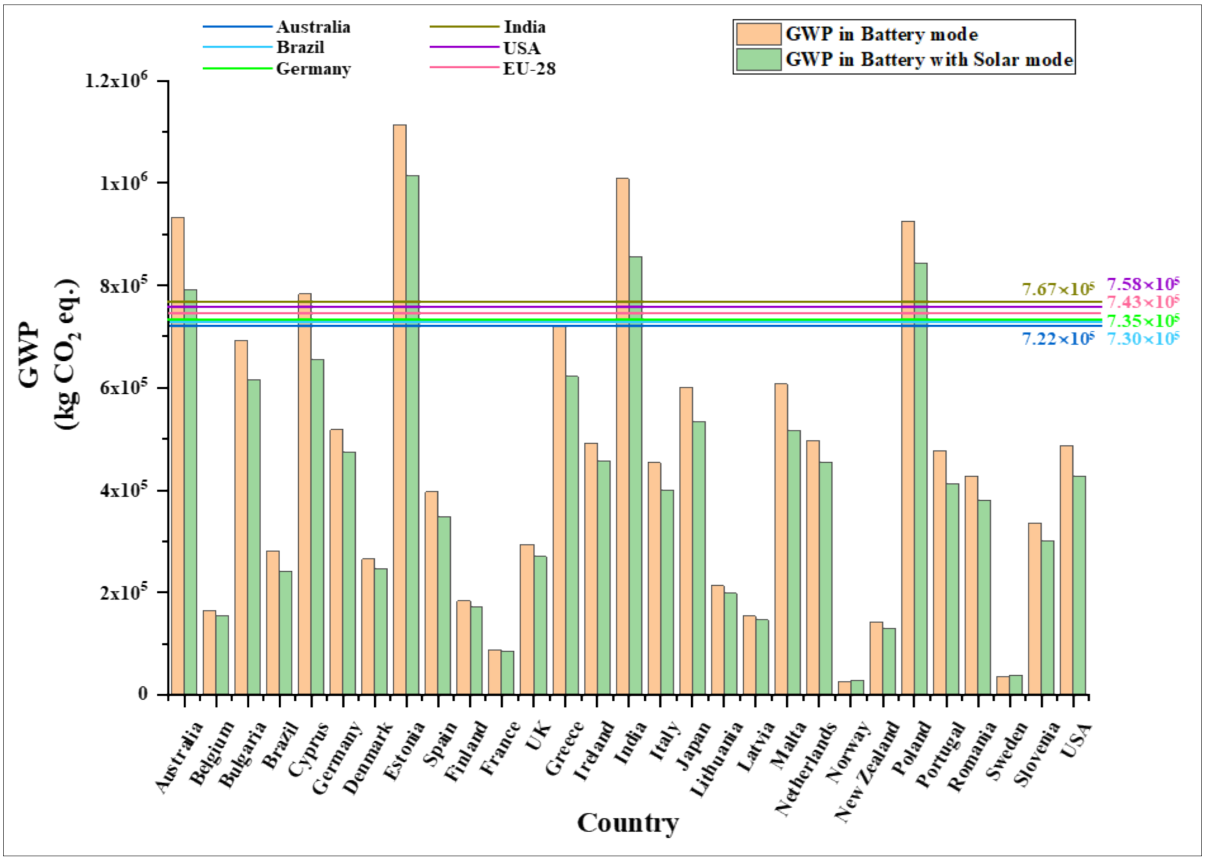


Figure 21. GWP values when 951,864 kWh is produced in each country with baselines from case 1

Results of Case 1 are used as baselines and those of Cases 2 and 3 were compared accordingly in Figure 21. In Australia, Estonia, India, and Poland, it can be seen that the case ship emits fewer GWPs with diesel operation rather than full battery cases both with/without solar power. This implies battery-powered ships may lead to more harmful environments than helpful. It may be hard to be classified as ‘green ship’ in the four subject countries. In Cyprus, it should be recognised that only EPS with the solar PV system could be more environmentally friendly than EPS only, compared to diesel operation.

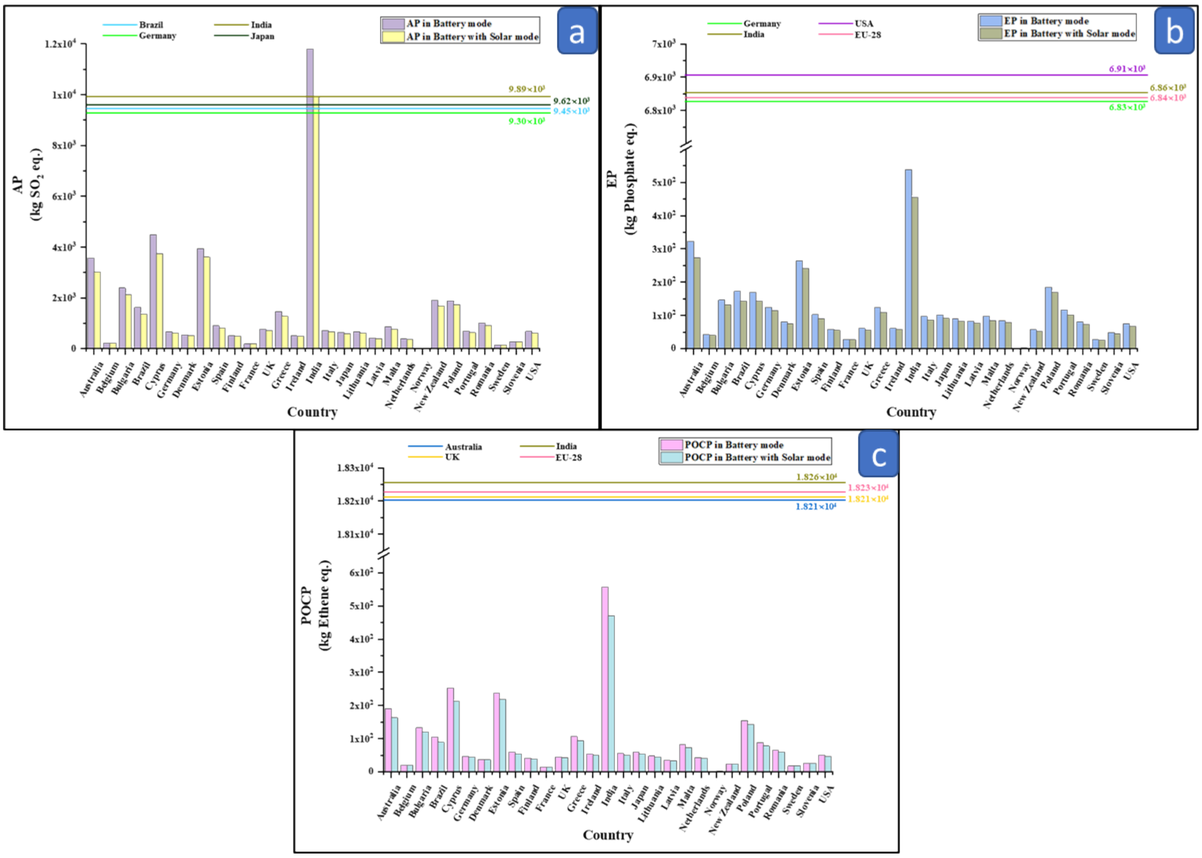


Figure 22. (a) AP, (b) EP and (c) POCP values when 951,864 kWh is produced in each country with baselines from case 1

As shown in Figure 22 (a), India has the highest level of AP which is far greater than Australia and Estonia with high coal usage for national electricity production, and Cyprus with high oil usage. Even the AP levels of India (both Case 2 and 3) were observed higher than diesel operation (Case 1). Currently, power generation in India is perceived as having more adverse environmental impacts when used battery-powered ships than conventional diesel ones. In terms of EP and POCP in Figure 22 (b) and (c), India also shows remarkably high impacts, but the figures for all countries remain below the baselines.

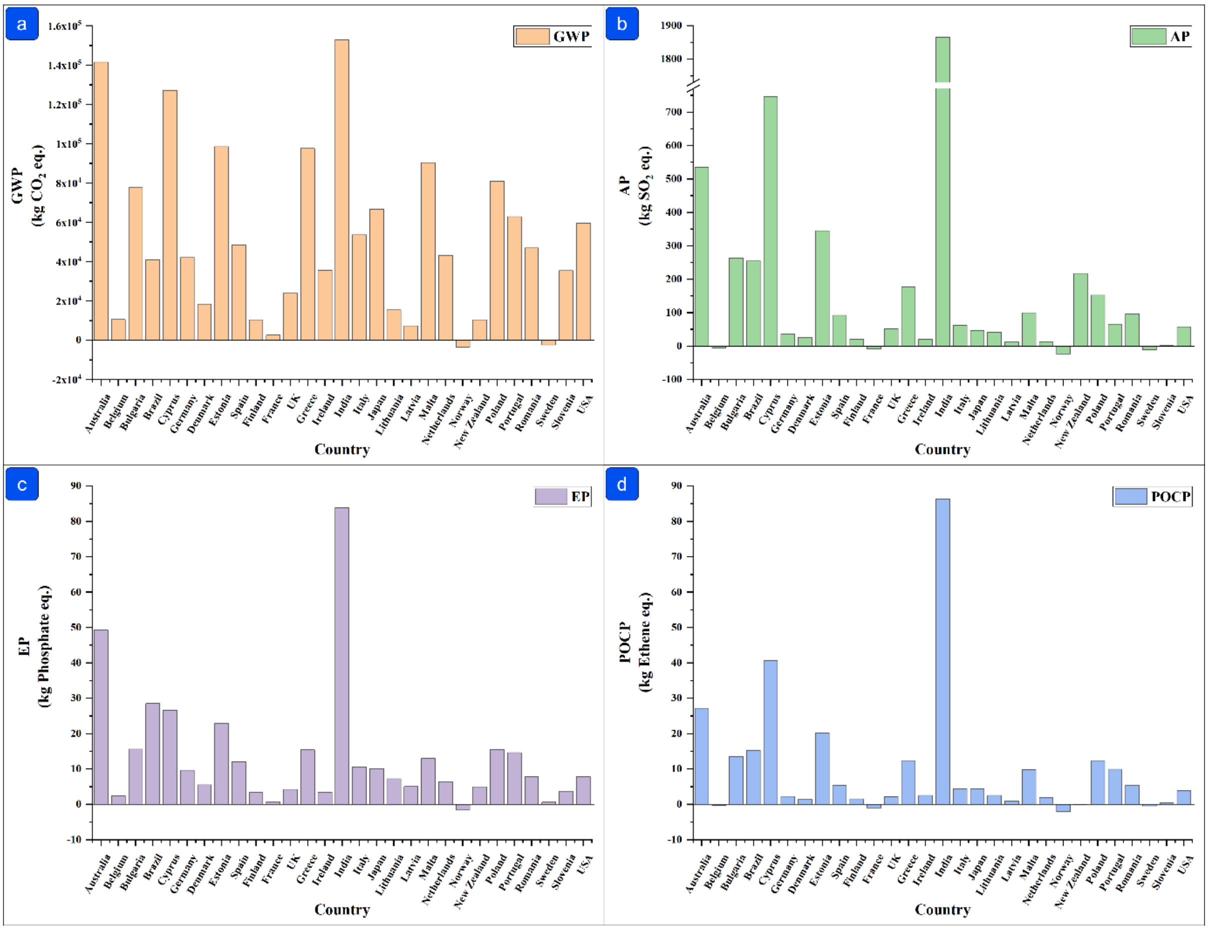


Figure 23. Differences of environmental impacts between Case 2 and Case 3

Furthermore, although the case ship can produce the most electricity using solar panels when it sails the coast of Brazil among the 29 countries surveyed, the amount of emission reduction is only 40,812 kg per year in terms of GWP. This is about 27% of saving 152,887 kg in India when operating the same vessel through solar panel installation, 29% of saving 141,517 kg in Australia, and 32% of saving 127,133 kg in Cyprus as shown in Figure 23. This has a significant indication in terms of how important it is to use which resources to generate electricity in the use of electric propulsion systems.

Overall, with the exception of some countries, such as Australia, Estonia, India, Poland and Cyprus, it can be viewed that powering EPS via AMP to the case ship is environmentally better than using conventional fuel in many countries. Nevertheless, this paper confirms that full battery ships do not ultimately guarantee zero-emission shipping and their environmental performances would be highly dependent on how to produce electricity and where to dispatch those ships.

3.2. Comparison with Conventional LCA

This section was prepared as a comparative analysis with the conventional LCA approach in order to present the excellence of LLCA. The conventional LCA, as discussed earlier, relies on the existing data without any prediction of different environmental performance along with experimental variables.

Based on the conventional LCA, solar panels installed on the case ship can produce up to 84.525 kW at 1000 W/m^2 and 25 conditions. Although irradiance varies greatly by region and month, the conventional LCA is intent to take some average values so that it can be assumed that approximately 40% of electric energy is produced, and if the annual power produced by the solar PV system is calculated with an estimated daylight time of about 10 hours: 123,406.5 kWh/year (84.525 kW × 40 % × 10 hours × 365 days).

Figure 24 compares the results of the amount of electricity produced by solar panels obtained from the conventional LCA to those from LLCA.

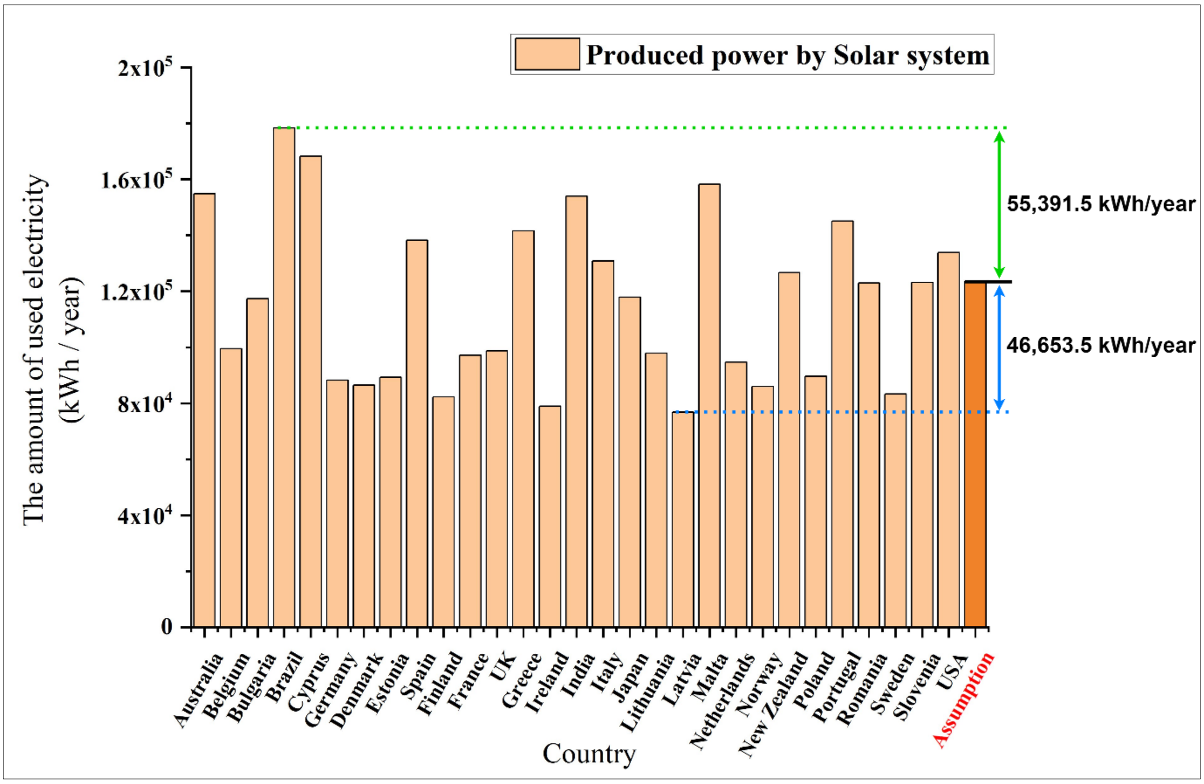


Figure 24. Amount of electricity produced by solar panels on the case ship by countries according to assumption and LLCA results

From Figure 24, it can be clearly seen that it is impossible to perform LCA in consideration of regional environmental factors with the existing LCA method. If LCA is performed after predicting electricity production through the solar PV system, inaccurate LCA results are obtained as shown in Figure 25 instead of the Live-LCA result in Figure 21 and Figure 22.

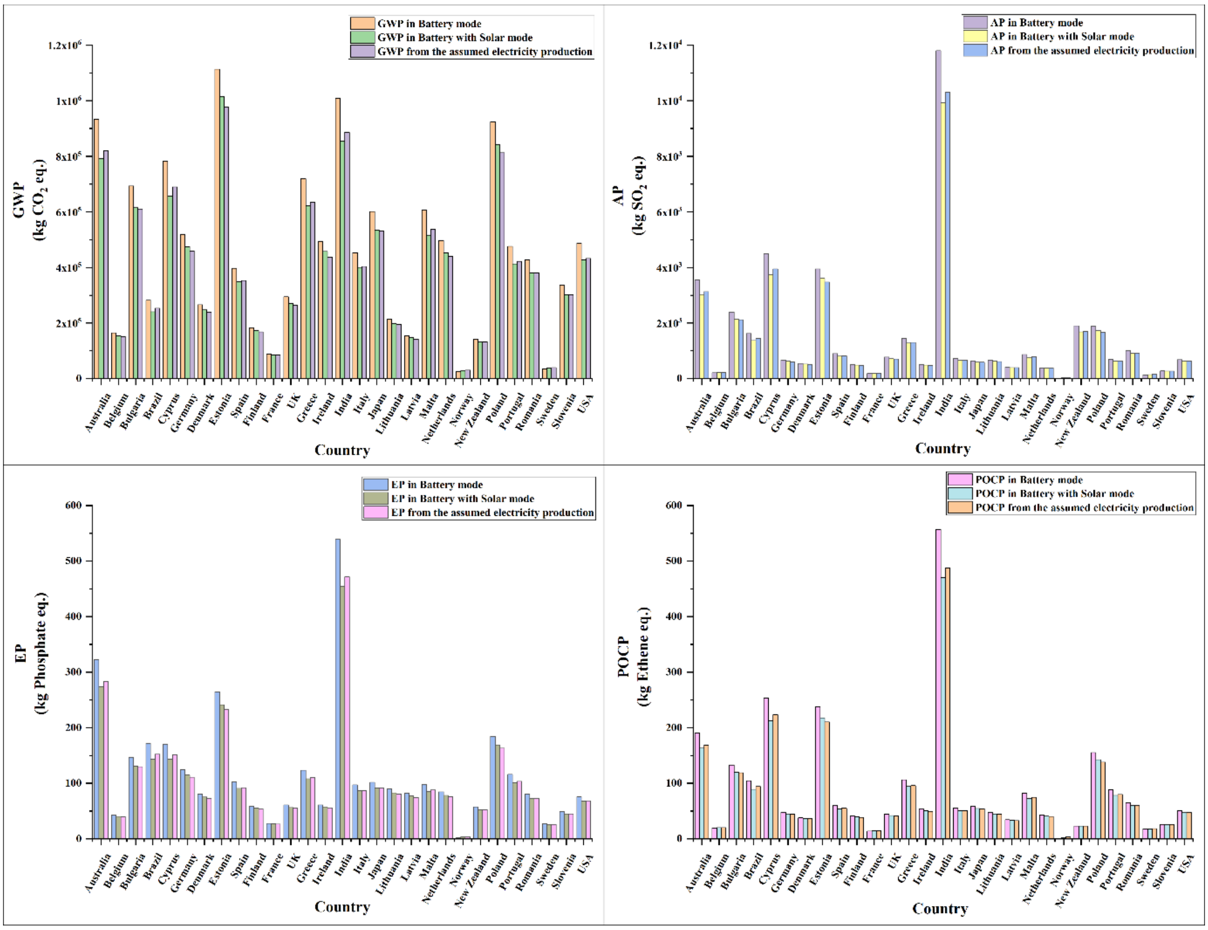


Figure 25. LCIA results by the country for Case 2, Case 3, and Case 3 assuming electricity production from solar panels

Figure 25 presents the gaps in analysis results between the conventional LCA and the LLCA.

Through the methodology of the conventional LCA, the electric power produced by the solar panel installed on the case ship was estimated to be 123,406.5 kWh/year, which corresponds to about 13.0% of the annual average electric power required for the ship. However, if the same operation is performed through LLCA, which can generate data and obtain accurate and reliable results according to the situation, the result can be obtained that the case ship can produce 178,798 kWh/year, the largest amount of electricity among the 29 countries surveyed, when it sails the coast of Brazil through solar panels. This amount of electricity corresponds to about 18.7% of the average annual power required of the vessel, and it is confirmed that it is produced about 44.5% more than the estimate when compared with the estimated power production through the conventional LCA. In addition, when it operates in Cyprus, 36.3% more electricity is generated compared to the estimated value through the conventional LCA, and 28.2% more electricity is generated when sailing in Malta. In the case of sailing in Romania and Slovenia, the electric energy actually produced by the solar panel is almost the same as the estimated output through the conventional LCA. However, when sailing in Latvia, the actual amount produced is 76,753 kWh per year by the solar panel, resulting in 37.8% less electricity than the estimated value, and 36.1% and 32.4% less electricity is produced when sailing in Ireland and Sweden, respectively. Therefore, when the existing LCA method is used instead of LLCA, it was confirmed that up to 44.5% of different energy production could be investigated in the case of this study. By substituting the result into the emission factor according to the electric energy production for each country, it is confirmed that 33,850 kg GWP per year is more generated when sailing Cyprus, and 30,356 kg GWP per year is emitted more in India when calculating the emission. In addition, in Estonia and Poland, 37,639 kg GWP and 30,540 kg GWP, respectively, are less generated which results are inaccurate.

When analyzing the inaccurate total annual GWP results through the conventional LCA and the accurate total annual GWP results through the LLCA, based on the conventional LCA results, in Brazil, Cyprus, Norway, and Ireland, it can be seen that 5.0%, 4.9%, 4.9%, and 4.6% different GWP generation results are obtained, respectively. That is, it has been proven that when LLCA is applied based on this case study, it is possible to derive up to 5% more accurate research results compared to the conventional LCA.

Through this, it can be verified once again that there are limitations to the existing LCA research, and that it is very important to obtain appropriate data through the Modelling/Setup & Simulation/Experiment process. Therefore, it is emphasized through this comparison that

LLCA becomes an important methodology for more accurate LCA performance that complements the limitations of conventional LCA studies.

3.3. Functional unit of the Electric propulsion ship

In Table 8, Index A shows the functional units for the case of refining marine gas oil (MGO) in each country and loading it on the fuel tank of a ship than using it. Index B represents the functional units in the case of sailing by supplying the electric energy produced in the relevant country to the battery of a ship. Index C describes the functional unit of solar panels that mean the lifecycle emissions for producing unit-electric power through the solar panel systems. In general, since the power generated by the solar PV system is not sufficient for ship operation, the power required in addition to the power generated by the solar PV system is supplied from the national grid through the AMP. Therefore, when an electric propulsion ship operates using power from batteries and the solar PV system together, the total emission value is calculated as the followed equation.

$$X = aY + bZ$$

X: Lifecycle environmental impacts of a ship using batteries and the solar PV system together
Y: Index B (Functional unit when a ship is supplied power from the national grid)
Z: Index C (Functional unit when a ship produces power by the solar PV system)
a: The amount of electric energy supplied from the national grid
b: The amount of electric energy produced by the solar PV system

With this equation, Table 8 and ship data, it is possible to perform LCA on all electric propulsion ships powered from the battery and electric propulsion ships to which solar PV system is applied, regardless of ship size or operational characteristics.

For example, if an electric propulsion ship without the solar PV system requiring 100,000 kW per year operates at the coast of the UK and is supplied electric power from there, it emits 30,900 kg GWP (100,000 × 0.309), 81 kg AP (100,000 × 0.00081), 6.39 kg EP (100,000 × 0.0000639), and 4.67 kg POCP (100,000 × 0.0000467) per year. Instead, if the solar PV system is installed on the same ship and it generates 20,000 kW per year in the same route, the ship emits 26,062 kg GWP (80,000 × 0.309 + 20,000 × 0.0671), 70.44 kg AP (80,000 × 0.00081 + 20,000 × 0.0002820), 5.534 kg EP (80,000 × 0.0000639 + 20,000 × 0.0000211), and 4.226 kg POCP (80,000 × 0.0000467 + 20,000 × 0.0000245) per year.

Table 8. Index of functional units

Index A: Functional unit when a ship uses diesel generators				
Unit: per L	GWP	AP	EP	POCP
Australia	3.62141	0.046999	0.034298	0.0912576
Brazil	3.66041	0.047359	0.034287	0.0912896
Germany	3.68241	0.046609	0.034246	0.0912866
UK	3.64241	0.046849	0.034259	0.0913016
India	3.84641	0.049589	0.034372	0.0915246
Japan	3.68041	0.048229	0.034423	0.0912836
USA	3.80141	0.046829	0.034625	0.0914056
EU-28	3.72541	0.047119	0.034290	0.0913776
Index B: Functional unit when a ship is supplied power from the national grid				
Unit: per kW	GWP	AP	EP	POCP
Australia	0.981	0.00374	0.000339	0.0002
Belgium	0.173	0.000221	0.0000449	0.0000207
Bulgaria	0.728	0.00252	0.000154	0.00014
Brazil	0.296	0.00171	0.000181	0.00011
Cyprus	0.823	0.00472	0.000179	0.000266
Germany	0.544	0.000694	0.000131	0.0000498
Denmark	0.279	0.000579	0.000085	0.0000399
Estonia	1.17	0.00415	0.000278	0.00025
Spain	0.417	0.000947	0.000108	0.0000629
Finland	0.193	0.000531	0.0000616	0.0000432
France	0.0928	0.000195	0.000029	0.0000144
UK	0.309	0.00081	0.0000639	0.0000467

Greece	0.756	0.00153	0.00013	0.000112
Ireland	0.518	0.000534	0.0000642	0.0000564
India	1.06	0.0124	0.000566	0.000585
Italy	0.477	0.000759	0.000102	0.0000581
Japan	0.632	0.00067	0.000107	0.0000621
Lithuania	0.225	0.000701	0.0000947	0.0000501
Latvia	0.162	0.00043	0.0000867	0.0000362
Malta	0.638	0.000913	0.000103	0.0000869
Netherlands	0.522	0.000406	0.000089	0.0000449
Norway	0.027	0.00000992	0.00000172	0.000000628
New Zealand	0.149	0.002	0.0000605	0.0000244
Poland	0.971	0.00198	0.000194	0.000163
Portugal	0.5	0.000732	0.000122	0.0000928
Romania	0.449	0.00106	0.0000845	0.0000687
Sweden	0.0375	0.000142	0.0000282	0.0000187
Slovenia	0.354	0.000288	0.0000513	0.0000277
USA	0.512	0.000715	0.0000795	0.0000536
Index C: Functional unit when a ship produces power by the solar PV system				
Unit: per kW	GWP	AP	EP	POCP
	0.0671	0.0002820	0.0000211	0.0000245

In terms of the case ship, the functional units when both battery and solar PV system are applied and when LCA of the case ship is performed through the conventional LCA could be obtained as shown in Table 9.

The bigger ships may have greater spaces for PV system installation so that it will produce more amount of electricity from the solar energy. Although this paper deals with a short-route ferry, the research findings clearly offer the index of functional units (Environmental impacts / kWh) which can also be applicable for larger ships as well. In fact, the index of the functional units proposed in this paper enables us to estimate the lifecycle environmental impacts of PV electric ships at any size.

Table 9. Functional unit of the case ship

Functional unit of the case ship (Full battery with solar PV mode) by LLCA

Unit: per kW	GWP	AP	EP	POCP
Australia	0.8323260	0.00317745	0.00028728	0.00017145
Belgium	0.1619368	0.00022737	0.00004241	0.00002110
Bulgaria	0.6464901	0.00224398	0.00013761	0.00012576
Brazil	0.2531237	0.00144251	0.00015105	0.00009398
Cyprus	0.6894383	0.00393584	0.00015110	0.00022333
Germany	0.4997817	0.00065580	0.00012081	0.00004745
Denmark	0.2597451	0.00055201	0.00007919	0.00003850
Estonia	1.0665548	0.00378721	0.00025390	0.00022885
Spain	0.3662014	0.00085046	0.00009538	0.00005733
Finland	0.1821134	0.00050947	0.00005810	0.00004158
France	0.0901788	0.00020387	0.00002819	0.00001543
UK	0.2839158	0.00075525	0.00005946	0.00004440
Greece	0.6534890	0.00134429	0.00011380	0.00009898
Ireland	0.4806164	0.00051311	0.00006063	0.00005376
India	0.8993817	0.01043971	0.00047785	0.00049433
Italy	0.4206686	0.00069345	0.00009088	0.00005348
Japan	0.5620243	0.00062194	0.00009636	0.00005744
Lithuania	0.2087647	0.00065792	0.00008713	0.00004747
Latvia	0.1543478	0.00041807	0.00008141	0.00003526
Malta	0.5431223	0.00080813	0.00008939	0.00007653
Netherlands	0.4767702	0.00039367	0.00008225	0.00004287
Norway	0.0306249	0.00003452	0.00000347	0.00000279
New Zealand	0.1381002	0.00177136	0.00005526	0.00002441
Poland	0.8858959	0.00182013	0.00017772	0.00014996
Portugal	0.4340334	0.00066343	0.00010662	0.00008239
Romania	0.3996825	0.00095953	0.00007631	0.00006299
Sweden	0.0400924	0.00015426	0.00002758	0.00001921
Slovenia	0.3168746	0.00028722	0.00004739	0.00002729
USA	0.4494223	0.00065410	0.00007129	0.00004951
Functional unit of the case ship by the conventional LCA				
Unit: per kW	GWP	AP	EP	POCP
Australia	0.8625154	0.00329168	0.00029779	0.00017725
Belgium	0.1592704	0.00022891	0.00004181	0.00002119
Bulgaria	0.6423162	0.00222985	0.00013677	0.00012503
Brazil	0.2663238	0.00152486	0.00016027	0.00009892
Cyprus	0.7249997	0.00414463	0.00015853	0.00023469
Germany	0.4821713	0.00064059	0.00011675	0.00004652
Denmark	0.2515278	0.00054049	0.00007672	0.00003790
Estonia	1.0270121	0.00364852	0.00024469	0.00022076
Spain	0.3716364	0.00086078	0.00009673	0.00005792
Finland	0.1766774	0.00049872	0.00005635	0.00004078
France	0.0894681	0.00020628	0.00002798	0.00001571
UK	0.2776383	0.00074155	0.00005835	0.00004382
Greece	0.6666860	0.00136820	0.00011588	0.00010066
Ireland	0.4595421	0.00050133	0.00005861	0.00005226

India	0.9312733	0.01082894	0.00049536	0.00051233
Italy	0.4238576	0.00069716	0.00009151	0.00005374
Japan	0.5587623	0.00061970	0.00009586	0.00005723
Lithuania	0.2045287	0.00064668	0.00008516	0.00004678
Latvia	0.1496965	0.00041081	0.00007820	0.00003468
Malta	0.5639844	0.00083119	0.00009238	0.00007881
Netherlands	0.4630235	0.00038992	0.00008020	0.00004226
Norway	0.0321989	0.00004519	0.00000423	0.00000372
New Zealand	0.1383819	0.00177727	0.00005539	0.00002441
Poland	0.8538119	0.00175986	0.00017158	0.00014504
Portugal	0.4438757	0.00067366	0.00010892	0.00008395
Romania	0.3994877	0.00095913	0.00007628	0.00006297
Sweden	0.0413376	0.00016015	0.00002728	0.00001945
Slovenia	0.3168042	0.00028722	0.00004738	0.00002729
USA	0.4543200	0.00065886	0.00007193	0.00004983

4. Discussion

4.1. Research Novelty

One of the fundamental limitations of conventional LCA approach is that it needs to be conducted with the data *‘we have’* not with the data *‘we want to have’*. Such limitations bear various uncertainties and assumptions while failing to present general application. On the other hand, LLCA, a new LCA practice, enables us to conduct LCA with the data *‘we want to have’* by “data generation process”. It will open up a new practice and standards for future LCA research, providing the great benefit to enhance the quality and the reliability of LCA studies with higher confidence.

The LLCA framework is believed to make sound contributions to improve LCA theory/practices as well as to extend the connection of LCA to different disciplines. In this regard, this paper is opening a new LCA standard, in particular to the marine industry. This paper firstly considered the dynamic features of marine systems systematically so that the relations among the inputs/data variations could be identified. The use of LLCA will contribute to determining the lifecycle solutions for future marine energy sources with higher accuracy and precision in consideration of real-time performances. Even, it is expected to offer effective information/guidelines for future maritime regulatory frameworks.

The indexes of functional units produced from the LLCA will be noticeably useful for ship designers, policy makers, and rule developers as providing environmental indicators with which anyone can obtain general trend and observation in relation between the characteristics of ships and systems and environmental impacts. Through the case study, this LLCA was demonstrated to answer the fundamental question on whether/when/where electric battery powered ships can ultimately be a promising solution for future maritime environmental protection; the conventional methods used to fail answering. While it is widely accepted that electric vehicles are an alternative to lowering fuel consumption and preventing air pollution [80], it has become evident that just adopting them cannot be the ultimate solution. This research strongly proposes that Australia, Estonia, India, and Poland make the shift to cleaner energy production before adopting electric automobiles and electric ships.

Research findings clearly suggest the misguidance of current maritime policies for developing battery-powered ships and identified these shortcomings would stem form the limitations and current maritime environmental assessment practices. In this context, research findings not only provide ship designers with an insight for enhancing the environmental sustainability of shipping but also suggesting a proper approach for maritime life cycle assessment for contributing to regulatory frameworks and guidelines.

4.2. Direction of future works

LCA research findings reveal that there may be numerous approaches to further reduce shipping emissions, implying that the overall environmental consequences are determined by a combination of various factors linked with upstream and downstream operations. Meanwhile, PV systems have been very limited applied for marine vessels up until now. Especially they are more often used for short-sea vessels rather than ocean-going ships. It is because of the technical hinderances and low energy density it can produce/carry. Because of the limitations of current technology, there is no large-capacity battery to be used properly for large ships such as ocean-going ships, and many solar panels cannot be installed onboard due to the characteristics of merchant ships. In general, 1 kW PV panel takes 8 m^2. A general ocean-going ship may have 200 m long and 30 m width so that it will have 6,000 m^2 on deck. So, even if laying PV panels throughout the whole deck, the subject ship can produce about 750 kW. Given that this ship requires more than 10,000 kW for propulsion power, the solar system onboard would be only able to cover 13% of the required power. As a result, no ocean-going ships can use PV systems for their propulsion power at current status. This is a key reason that why this paper was convinced to be focused on a small-scaled short sea ferry rather than ocean going ships with PV systems, which are not realistic applications at the current technological status. Considering the limitation of PV systems onboard, this paper may highlight the benefits of electric propulsion ships that offer significant advantages in terms of easy coupling with diverse technologies, the existing system still has considerable opportunity for further improvement in system optimization. As a result, it will be critical to expand research into ways to generate less or even net-zero emissions through efficient energy supply/production, such as the use of onboard fuel cells.

5. Conclusions

The results and key messages of this study are as follows.

1) This paper fundamentally suggests the new methodology called Live-Life Cycle Assessment which is a simulation-based research technique that allows for more precise data collection and can apply to universal life cycle assessment studies. The results of the study using this technique provide a different view quantitatively and intuitively about the general perception on whether electric propulsion ships are completely green ships or not, which will be noticeably useful for ship designers, ship owners, rule developers and policymakers. In this context, the research results not only provide insights for improving the environmental sustainability of ships, but also underscore the importance of approaching electric propulsion ships from a life cycle assessment perspective.
2) From the holistic point of view, this paper improved the LCA study, which was case-specific, using fragmentary and limited data, to LLCA study, so that more accurate LCA results can be obtained by securing appropriate data according to the situation. In addition, as a study that can be applied to various ships, a methodology that can be used regardless of the scope of application was presented.
3) When environmental pollutants generated to produce 1 kW of electricity in the country were investigated into four categories, GWP, AP, EP, and POCP, Australia, Estonia, India and Poland were identified as generating the most pollutants. In terms of GWP, Estonia showed more emissions than India, but in terms of AP, EP, and POCP, India was found to have overwhelmingly higher emissions than other countries.
4) When the production and transportation of MGO are considered comprehensively in terms of LCA, and the case ship produces electricity through diesel generators using

that MGO and operates it, India is the country that has the most figure in GWP, AP, and POCP among the surveyed eight countries. In addition, the US ranks second after India in the GWP, and shows the most involvement in the EP.

5) Through the solar panels installed on the case ship, it is possible to produce 84.525 kWh of electrical energy at the maximum in the weather condition of 1000 W/m2 and 25 , which shows a markedly different amount of electricity generation depending on the environmental factors where the case ship operates. Looking at the annual electricity production through the solar panels installed on the case ship, it produces the largest amount of 178,298 kWh when sailing along the coast of Brazil, 168,187 kWh when sailing in Cyprus, and the lowest of 76,753 kWh when sailing on the coast of Latvia.
6) Most of the electric propulsion vessels sailing using electricity produced in the 29 countries surveyed showed better environmental results than electric propulsion vessels operated by generating electricity using diesel generators. However, in terms of GWP, it was found that electric propulsion vessels sailing in full battery mode performed worse when they were supplied with electricity from Australia, Cyprus, Estonia, India and Poland than when they generated electricity on their own. diesel generator. Even when solar power systems were applied to ships, GWP was still high in four countries except for Cyprus.
7) LCA results showed a significantly different trend depending on the energy production method of each country. Therefore, this study provided a basis for judging whether electric drive systems using electricity produced in that country are more environmentally friendly than those using existing fossil fuels.
8) In this study, the result of 'Not always' was drawn to the fundamental question of "Can electric propulsion ships be called eco-friendly ships in all countries and regions?" This means that reducing the number of ships using fossil fuels and replacing them with

electric propulsion ships has limitations in terms of environmental protection. Therefore, since the environmental impact varies greatly depending on the electric energy production method and power generation source, it is necessary to continuously discuss how to convert it to an eco-friendly environment.

Acknowledgement

This research is part of the Clean Maritime Demonstration Competition, funded by the Department for Transport of the UK and delivered in partnership with Innovate UK [Project no. 10004404]. The authors wish to thank to University of Strathclyde as providing one of the authors with financial support for pursuing PhD. We also must express our gratitude to Lloyds Register for their willingness to share meaningful data for our research.

References

[1] Ortiz-Ospina E, Beltekian D, Roser M. Trade and globalization. Our World in Data. 2018.

[2] The World Bank. GDP. 2021.

[3] Singh SP, Saha K, Singh J, Sandhu A. Measurement and analysis of vibration and temperature levels in global intermodal container shipments on truck, rail and ship. Packaging Technology and Science. 2012;25:149-60.

[4] International Chamber of Shipping. Shipping, world trade and the reductions of CO2 emissions. International Chamber of Shipping London, UK; 2014.

[5] Scott M. Sustainable shipping is making waves. The Guardian. 2014.

[6] Sustainable Shipping Initiative. Vision 2040. Sustainable Shipping Initiative; 2011.

[7] United Nation Conference on Trade and Development (UNCTAD). Merchant fleet by flag of registration and by type of ship, annual. 2020.

[8] Micco A, Pérez N. Maritime transport costs and port efficiency. Inter-American Development Bank Washington, DC. 2001.

[9] International Maritime Organization (IMO). Third IMO GHG Study. International Maritime Organization; 2014.

[10] International Maritime Organization (IMO). Fourth IMO GHG Study. International Maritime Organization; 2020.

[11] International Maritime Organization. Prevention of Air Pollution from Ships. 2021.

[12] Perčić M, Vladimir N, Fan A. Life-cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short-sea shipping: A case study of Croatia. Applied Energy. 2020;279:115848.

[13] DNV GL. Alternative fuels in the Arctic. 2019.

[14] Vahabzad N, Jadidbonab M, Mohammadi-Ivatloo B, Tohidi S, Anvari-Moghaddam A. Energy management strategy for a short-route hybrid cruise ship: an IGDT-based approach. IET Renewable Power Generation. 2020;14:1755-63.

[15] DNV GL. Maritime forecast to 2050. Energy Transition Outlook. 2018.

[16] Kanellos FD, Anvari-Moghaddam A, Guerrero JM. Smart shipboard power system operation and management. Inventions. 2016;1:22.

[17] Lee DK, Jeong Y-K, Shin JG, Oh D-K. Optimized design of electric propulsion system for small crafts using the differential evolution algorithm. International Journal of Precision Engineering and Manufacturing-Green Technology. 2014;1:229-40.

[18] Yang L, Cai Y, Yang Y, Deng Z. Supervisory long-term prediction of state of available power for lithium-ion batteries in electric vehicles. Applied Energy. 2020;257:114006.

[19] Hansen JF, Wendt F. History and state of the art in commercial electric ship propulsion, integrated power systems, and future trends. Proceedings of the IEEE. 2015;103:2229-42.

[20] Pestanam H. Future Trends of Electric Propulsion and Implications to Ship Design. Proc Martech. 2014.

[21] Chai M, Bonthapalle DR, Sobrayen L, Panda SK, Wu D, Chen X. Alternating current and direct current-based electrical systems for marine vessels with electric propulsion drives. Applied Energy. 2018;231:747-56.

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

[23] Doorduin W, Witlox L, Lageweg M, van Brakel R. The use of electric motors for the propulsion of seagoing vessels. Rotterdam Mainport University of Applied Sciences (RMU). 2013.

[24] Sadr S, Khanzade MH. Ship Electrical Propulsion System. Journal of Basic and Applied Scientific Research. 2013;3:655-60.

[25] Wei M, Lee SH, Hong T, Conlon B, McKenzie L, Hendron B, et al. Approaches to cost-effective near-net zero energy new homes with time-of-use value of energy and battery storage. Advances in Applied Energy. 2021;2:100018.

[26] Amabile L, Bresch-Pietri D, El Hajje G, Labbé S, Petit N. Optimizing the self-consumption of residential photovoltaic energy and quantification of the impact of production forecast uncertainties. Advances in Applied Energy. 2021;2:100020.

[27] Li P, Zhang H, Guo Z, Lyu S, Chen J, Li W, et al. Understanding rooftop PV panel semantic segmentation of satellite and aerial images for better using machine learning. Advances in Applied Energy. 2021;4:100057.

[28] Schleifer AH, Murphy CA, Cole WJ, Denholm PL. The evolving energy and capacity values of utility-scale PV-plus-battery hybrid system architectures. Advances in Applied Energy. 2021;2:100015.

[29] Marqusee J, Becker W, Ericson S. Resilience and Economics of Microgrids with PV, Battery Storage, and Networked Diesel Generators. Advances in Applied Energy. 2021:100049.

[30] Li Y, Vilathgamuwa M, Xiong B, Tang J, Su Y, Wang Y. Design of minimum cost degradation-conscious lithium-ion battery energy storage system to achieve renewable power dispatchability. Applied Energy. 2020;260:114282.

[31] Wen S, Lan H, Hong Y-Y, David CY, Zhang L, Cheng P. Allocation of ESS by interval optimization method considering impact of ship swinging on hybrid PV/diesel ship power system. Applied energy. 2016;175:158-67.

[32] ABS. Ship energy efficiency measures advisory. American Bureau of Shipping Houston (TX); 2017.

[33] Nguyen XP, Dong VH. A study on traction control system for solar panel on vessels. AIP Conference Proceedings: AIP Publishing LLC; 2020. p. 020016.

[34] Lee K-J, Shin D, Yoo D-W, Choi H-K, Kim H-J. Hybrid photovoltaic/diesel green ship operating in standalone and grid-connected mode–Experimental investigation. Energy. 2013;49:475-83.

[35] Nasirudin A, Chao R-M, Utama IKAP. Solar powered boat design optimization. Procedia engineering. 2017;194:260-7.

[36] Nuchturee C, Li T, Xia H. Energy efficiency of integrated electric propulsion for ships–A review. Renewable and Sustainable Energy Reviews. 2020;134:110145.

[37] Kim K, Park K, Ahn J, Roh G, Chun K. A study on applicability of Battery Energy Storage System (BESS) for electric propulsion ships. 2016 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific): IEEE; 2016. p. 203-7.

[38] Lim C-o, Park B-c, Lee J-c, Kim ES, Shin S-c. Electric power consumption predictive modeling of an electric propulsion ship considering the marine environment. International Journal of Naval Architecture and Ocean Engineering. 2019;11:765-81.

[39] Hansen JF, Lindtjørn JO, Vanska K, Abb O. Onboard DC Grid for enhanced DP operation in ships. Dynamic Positioning Conference, Houston2011.

[40] Thantirige K, Rathore AK, Panda SK, Jayasignhe G, Zagrodnik MA, Gupta AK. Medium voltage multilevel converters for ship electric propulsion drives. 2015 International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles (ESARS): IEEE; 2015. p. 1-7.

[41] Hou J, Sun J, Hofmann HF. Mitigating power fluctuations in electric ship propulsion with hybrid energy storage system: Design and analysis. IEEE Journal of Oceanic Engineering. 2017;43:93-107.

[42] Glykas A, Papaioannou G, Perissakis S. Application and cost–benefit analysis of solar hybrid power installation on merchant marine vessels. Ocean Engineering. 2010;37:592-602.

[43] Kaisha NYK, Kyokai NK. World's First Solar-Power-Assisted Vessel Further Developed-Car Carrier Auriga Leader to be Fitted with Hybrid Power Supply System and Ballast-Water Management System, and Adapted to Use Low-Sulfur Fuel. Retrieved May. 2011;25:2011.

[44] GEORGE C, MIHAELA CC. CONTROL SYSTEM FOR SHIP SOLAR TRACKER.

[45] Rivela B, Montero A, Criollo B, Vaca D, López-Villada J. Environmental Policies in Maritime Transport: A Case Study of Solar Ship in Galapagos Islands. 2015.

[46] Peng C, Shounan S, Hai L, Qiang Z. Modeling and simulation of ship power system integration of solar energy. 2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific): IEEE; 2014. p. 1-5.

[47] Lan H, Wen S, Hong Y-Y, David CY, Zhang L. Optimal sizing of hybrid PV/diesel/battery in ship power system. Applied energy. 2015;158:26-34.

[48] Zhang Y, Yuan C, Li H, Yang T. A optimization method used for sailing route of solar ship. 2017 4th International Conference on Transportation Information and Safety (ICTIS): IEEE; 2017. p. 541-4.

[49] Tang R. Large-scale photovoltaic system on green ship and its MPPT controlling. Solar Energy. 2017;157:614-28.

[50] Yuan Y, Wang J, Yan X, Li Q, Long T. A design and experimental investigation of a large-scale solar energy/diesel generator powered hybrid ship. Energy. 2018;165:965-78.

[51] Yuan Y, Zhang T, Shen B, Yan X, Long T. A fuzzy logic energy management strategy for a photovoltaic/diesel/battery hybrid ship based on experimental database. Energies. 2018;11:2211.

[52] Vahabzad N, Mohammadi-Ivatloo B, Anvari-Moghaddam A. Optimal energy scheduling of a solar-based hybrid ship considering cold-ironing facilities. IET Renewable Power Generation. 2021;15:532-47.

[53] Atodiresei D, Nicolae F, Cotorcea A. Cost-benefit analysis of photovoltaic systems installed on ships on the trade routes in the northwest Black Sea basin. Journal of Environmental Protection and Ecology. 2017;18:40-5.

[54] Turconi R, Boldrin A, Astrup T. Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renewable and sustainable energy reviews. 2013;28:555-65.

[55] Qiao Q, Zhao F, Liu Z, Jiang S, Hao H. Cradle-to-gate greenhouse gas emissions of battery electric and internal combustion engine vehicles in China. Applied Energy. 2017;204:1399-411.

[56] Demir N, Taşkın A. Life cycle assessment of wind turbines in Pınarbaşı-Kayseri. Journal of Cleaner Production. 2013;54:253-63.

[57] Byrnes TA, Dunn RJ. Boating-and Shipping-Related Environmental Impacts and Example Management Measures: A Review. Journal of Marine Science and Engineering. 2020;8:908.

[58] Jeong B, Jeon H, Kim S, Kim J, Zhou P. Evaluation of the lifecycle environmental benefits of full battery powered ships: Comparative analysis of marine diesel and electricity. Journal of Marine Science and Engineering. 2020;8:580.

[59] Klöpffer W. Introducing life cycle assessment and its presentation in ‘LCA Compendium’. Background and future prospects in life cycle assessment: Springer; 2014. p. 1-37.

[60] Ellingsen H, Fet A, Aanondsen S. Tool for environmental efficient ship design. Paper at ENSUS. 2002.

[61] Kameyama M, Hiraoka K, Sakurai A, Naruse T, Tauchi H. Development of LCA software for ships and LCI analysis based on actual shipbuilding and operation. Proc 6 th Int Conf on Ecobalance: Citeseer; 2005.

[62] Kameyama M, Hiraoka K, Tauchi H. Study on life cycle impact assessment for ships. Tokyo, Japan. 2007.

[63] Popa C, Florin N, Haralambie B. Applications of life cycle assessment (LCA) in shipping industry. SGEM2014 Conference Proceedings2014.

[64] Chatzinikolaou SD, Ventikos NP. Applications of life cycle assessment in shipping. 2nd International Symposium on Naval Architecture and Maritime, Istanbul, Turkey2014.

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

[66] Bilgili L. Life cycle comparison of marine fuels for IMO 2020 Sulphur Cap. Science of The Total Environment. 2021;774:145719.

[67] Hwang S, Jeong B, Jung K, Kim M, Zhou P. Life cycle assessment of LNG fueled vessel in domestic services. Journal of Marine Science and Engineering. 2019;7:359.

[68] El-Houjeiri H, Monfort JC, Bouchard J, Przesmitzki S. Life cycle assessment of greenhouse gas emissions from marine fuels: a case study of Saudi crude oil versus natural gas in different global regions. Journal of Industrial Ecology. 2019;23:374-88.

[69] Wang H, Oguz E, Jeong B, Zhou P. Life cycle and economic assessment of a solar panel array applied to a short route ferry. Journal of Cleaner Production. 2019;219:471-84.

[70] Ling-Chin J, Roskilly AP. A comparative life cycle assessment of marine power systems. Energy Conversion and Management. 2016;127:477-93.

[71] Ma H, Steernberg K, Riera-Palou X, Tait N. Well-to-wake energy and greenhouse gas analysis of SOX abatement options for the marine industry. Transportation Research Part D: Transport and Environment. 2012;17:301-8.

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

[73] Jang H, Jeong B, Zhou P, Ha S, Nam D. Demystifying the lifecycle environmental benefits and harms of LNG as marine fuel. Applied Energy. 2021;292:116869.

[74] Karimi S, Zadeh M, Suul JA. Shore Charging for Plug-In Battery-Powered Ships: Power System Architecture, infrastructure, and Control. IEEE Electrification Magazine. 2020;8:47-61.

[75] Kim K, Park K, Roh G, Chun K. DC-grid system for ships: a study of benefits and technical considerations. Journal of International Maritime Safety, Environmental Affairs, and Shipping. 2018;2:1-12.

[76] Geertsma R, Negenborn R, Visser K, Hopman J. Design and control of hybrid power and propulsion systems for smart ships: A review of developments. Applied Energy. 2017;194:30-54.

[77] Zhou H, Bhattacharya T, Tran D, Siew TST, Khambadkone AM. Composite energy storage system involving battery and ultracapacitor with dynamic energy management in microgrid applications. IEEE transactions on power electronics. 2010;26:923-30.

[78] Ovrum E, Bergh T. Modelling lithium-ion battery hybrid ship crane operation. Applied Energy. 2015;152:162-72.

[79] Kularatna N. Energy storage devices for electronic systems: rechargeable batteries and supercapacitors: Academic Press; 2014.

[80] Song Z, Feng S, Zhang L, Hu Z, Hu X, Yao R. Economy analysis of second-life battery in wind power systems considering battery degradation in dynamic processes: Real case scenarios. Applied Energy. 2019;251:113411.

[81] Maheshwari A, Paterakis NG, Santarelli M, Gibescu M. Optimizing the operation of energy storage using a non-linear lithium-ion battery degradation model. Applied Energy. 2020;261:114360.

[82] Buchmann I. Batteries in a portable world: a handbook on rechargeable batteries for non-engineers. fourth ed: Cadex Electronics; 2017.

[83] International Energy Agency (IEA). Monthly OECD Electricity Statistics. 2020.