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Original Article

대한민국의 청정 해운을 위한 태양광 시스템 제어 기능을 갖춘 전기 추진 선박의 실효성

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Effectiveness of Electric Propulsion Ship with Solar PV Control Toward Cleaner Shipping in South Korea

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요 약

심각해지는 환경 문제에 대응하고 지속적으로 강화되는 규제에 대한 대안으로 전기 추진 시스템과 태양광 발전 시스템이 해운 산업에 도입되고 있다. 본 연구는 선박용 경유(MGO)를 연료로 하는 기계식 추진 선박과 비교하여 전기 추진 선박과 최대 전력점 추적(MPPT) 알고리즘으로 제어되는 태양광 발전 시스템이 통합된 선박의 환경적 이점을 정량적으로 평가하는 것을 목표로 한다. 이를 위해 MATLAB/Simulink을 이용하여 전기 추진 시스템과 최대 전력점 추적 알고리즘을 적용한 태양광 발전 시스템 모델링을 수행하였다. 그 결과, 대한민국에서 조업하는 소형 어선을 전기 추진 시스템으로 전환 시 40% 이상의 지구 온난화 영향 감소 효과를 얻을 수 있는 것으로 확인되었다. 또한, 본 연구는 이러한 연구 결과를 넘어서서 다른 국가의 전력 시스템과 비교하여 대한민국의 전기 추진 시스템 적용에 대한 통찰력을 제공한다. 이는 다양한 이해관계자들에게 대한민국 에너지 산업의 현주소를 알리고 향후 방향성을 제공하는 유의미한 역할을 할 수 있다.

Abstract – Electric propulsion systems and Solar PV systems are being introduced into the maritime industry as alternatives to address environmental concerns and to meet strengthening regulations. This study aims to quantitatively assess the environmental advantages of the electric propulsion ship and Solar PV system controlled by MPPT algorithm in comparison to the conventional MGO-fuelled mechanical propulsion ship. To achieve this goal, modelling of the electric propulsion system and MPPT-applied Solar PV system through MATLAB/Simulink was conducted. As a result, it was confirmed that transitioning small fishing boats operating in South Korea to the electric propulsion system can achieve over 40% less global warming effects. Furthermore, this study goes beyond these findings by providing insights into the application of electric propulsion systems in South Korea compared to other countries' power systems. It offers guidance for various stakeholders and suggests directions for future developments.

Keywords: Electric propulsion ship(전기 추진 선박), Solar PV(태양광 발전), Maximum power point tracking (최대 전력점 추적), Life cycle assessment(전과정 평가), Decarbonising shipping(해운 탈탄소화), Alternative energy(대체 에너지)

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1. Introduction

1.1 Overview

Global energy demand continues its upward trajectory, with a substantial 81.3% of the global energy supply being dependent on fossil fuels, notably oil, as of 2018. Notably, the maritime sector plays a significant role, contributing 6.8% to the overall energy consumption (Bilgili[2023]). Consequently, in 2018, the greenhouse gas (GHG) emissions resulting from maritime activities amounted to 1,076 million tons of carbon dioxide equivalent (CO_2 eq.), reflecting a 9.3% increase compared to the levels observed in 2012. Ships are also accountable for 2.89% of the total anthropogenic emissions globally (International Maritime Organization[2020]).

In the shipping sector, the International Maritime Organization (IMO) has a responsibility for addressing these critical environmental challenges. The IMO is presently implementing rigorous regulations to pave the way for a more environmentally sustainable future in shipping, as indicated by recent research conducted within the framework of the International Convention for the Prevention of Pollution from Ships (MARPOL) (Gilbert *et al.*[2018]).

Illustratively, two notable amendments to MARPOL ANNEX VI include the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). These regulations are designed to enhance the efficiency of ships and facilitate comparisons in terms of energy efficiency. Key indicators such as EEDI and Energy Efficiency Operating Indicator (EEOI) employ multivariate equations to evaluate a ship's CO_2 emissions during both the design phase and operational phases (Livanos *et al.*[2014]). Of particular significance is the introduction of supplementary tools by the IMO during the 76th MEPC meeting in June 2021. These tools, including the Energy Efficient Existing Ships Index (EEXI) and the Carbon Intensity Index (CII), are aimed at further improving energy efficiency (DNV[2021]; DNV GL[2020]).

1.2 Effectiveness of Electric propulsion and Solar PV system

Numerous strategies have been proposed to adhere to the regulations established by the IMO and mitigate emissions from ships. Within this array of solutions, electric propulsion and solar photovoltaic (PV) systems have emerged as viable alternatives, gaining prominence in the market (Symington *et al.*[2016]). Subsequently, a concerted research effort also has been spotlighted to advance sustainable maritime transportation by integrating renewable energy systems, notably solar power with fuel cells. These efforts have resulted in an increased adoption of renewable energy systems, resulting in reduced greenhouse gas emissions when compared to conventional diesel-only systems (Ghenai *et al.*[2019b]).

In contrast to alternative energy sources, solar panels, which utilise sunlight to produce electrical energy, typically exhibit a low range of efficiency. Continuous scholarly inquiry and developmental endeavours encompass a multitude of facets aimed at enhancing the operational effectiveness of PV panel systems and mitigating associated challenges. These encompass a diverse array of solar PV system configurations and control systems such as Maximum Power Point Tracking (MPPT), demonstrating the interdisciplinary nature of the ongoing research in this field (Pakkiraiah and Sukumar[2016]).

To address this research gap, scholars embarked on a comprehensive investigation and comparative analysis of various electric propulsion systems actively employed in commercial maritime vessels. The overarching objective was to discern the most suitable power management techniques that could augment the efficiency of solar power systems. Multiple research studies have been undertaken in pursuit of this objective. In order to bolster the efficiency of the solar power system itself, investigations have concentrated on the design and control methodologies of solar PV systems that integrate solar power modular multi-level inverters (MMI) or multi-level inverters (MLI) tailored for marine applications. This approach has been rigorously substantiated to not only contribute to the amelioration of system efficiency but also to markedly curtail energy losses (Gnanavel *et al.*[2021]; Shi and Luo[2018]).

Furthermore, through an investigation involving the implementation of a hybrid solar/fuel cell power system on a ferry vessel, the hybrid power arrangement, encompassing a fuel cell, solar panel, and diesel generator, successfully harnessed a substantial proportion of renewable energy, constituting 20% of the total power output. Simultaneously, a notable reduction in greenhouse gas emissions was observed in comparison to conventional diesel engines (Ghenai *et al.*[2019]). An analogous examination was also conducted, assessing the feasibility of installing a solar array configuration on a roll-on/roll-off (Ro-Ro) vessel operating between Pendik, Turkey, and Trieste, Italy. The solar PV system, in this context, achieved an impressive energy efficiency rating of 7.76%. Importantly, this implementation led to a significant decrease in emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon dioxide (CO_2), and particulate matter (PM) (Karatuğ and Durmuşoğlu[2020]).

As global research endeavours intensify to advance electric propulsion ships integrated with solar PV systems in regions such as Europe, the United States, and China, a notable research deficiency exists concerning ships operating within the maritime confines of South Korea. This inadequacy has emerged as a fundamental question of whether there will be environmental benefits if ships based in South Korea operate based on the electric propulsion system with/without solar PV system.

1.3 Necessity of LCA for marine applications

Amidst the ongoing research efforts focused on electric propulsion ships integrated with solar PV technology, there exists a need to definitively establish the environmental effectiveness of such vessels. The existing body of scholarly work consistently emphasises the environmentally beneficial characteristics of ships equipped with solar PV systems (Karatuğ and Durmuşoğlu [2020]; Yuan *et al.*[2021]). These vessels are demonstrated to have the capability to significantly reduce CO_2 emissions and generate noteworthy cost savings when juxtaposed with their diesel-powered counterparts. Moreover, with the rapid advancements in battery and solar PV technologies, it is anticipated that the development of solar-powered ships will play a pivotal role in significantly mitigating greenhouse gas emissions (Leung and Cheng[2017]). The findings from these investigations demonstrate that maritime operations incorporating not only solar power generation but also wind and wave energy sources manifest reduced fuel consumption, thereby fostering more eco-conscious and sustainable sea transportation practices (Rutkowski[2016]). In a parallel vein, research has unveiled that the deployment of hybrid PV, wind, and fuel cell energy systems on tankers can lead to noteworthy reductions in CO_2 emissions alongside tangible economic advantages (Huang *et al.*[2021]).

Nevertheless, research indicates that electric energy may not consistently align with environmental friendliness when considering the complete life cycle (Jeong *et al.*[2022]). As clearly shown in Fig. 1, the level of emissions associated with electrical energy varies significantly depending on the source of energy used for electricity generation (National Renewable Energy Lab.[2021]).

Hence, it is imperative to move beyond the conventional, narrow assessment focused on emission reduction in the usage phase and conduct a more comprehensive scrutinise of technologies such as electric propulsion systems and solar power generation from a holistic life cycle perspective.

Amid increasingly stringent environmental regulations, the Carbon Intensity Index (CII) has emerged as a compelling regulatory framework. However, even this rigorous regulation has clear limitations in contributing to realising substantive environmental improvements when compared to the Life Cycle Assessment (LCA) framework. As illustrated in Fig. 2, the scope of CII is relatively limited as only focuses on CO_2 excluding other emissions, and mainly addresses the fuel consumption phase ignoring the preceding phases of fuel production. As a result, it is difficult to determine actual environmental friendliness based on current environmental regulations.

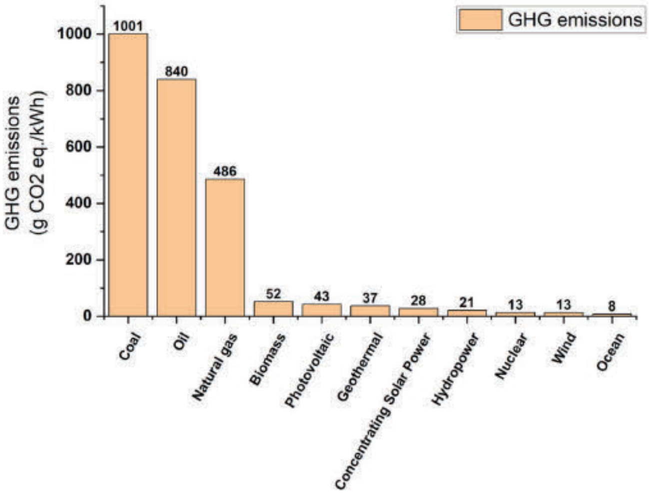
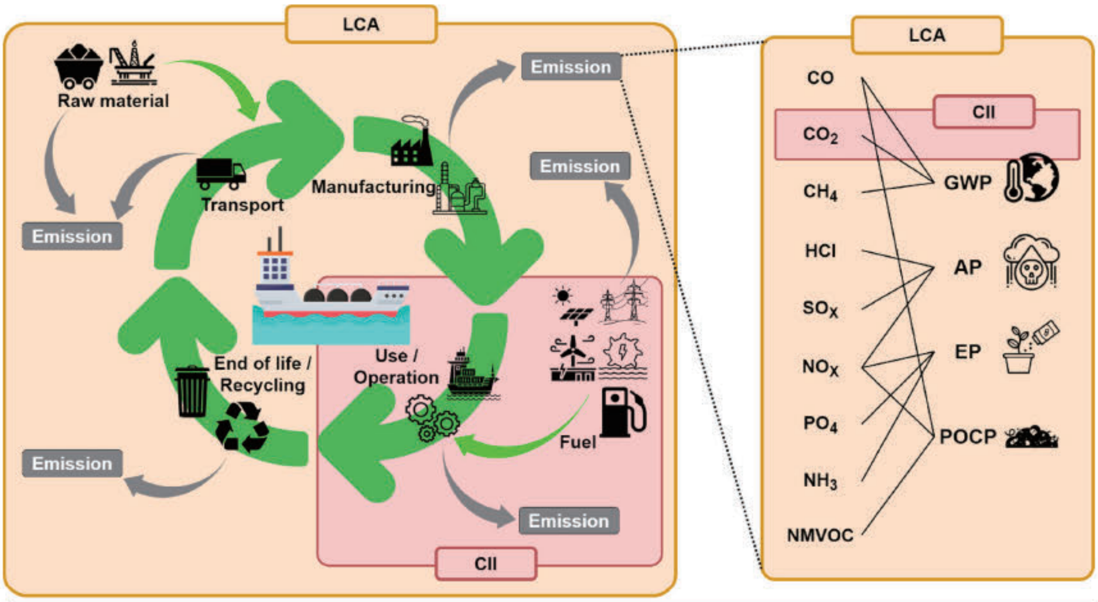


Fig. 1. GHG emissions by energy sources when producing electricity.

Given the insufficient comprehensive environmental assessment that encompasses the importance of electric propulsion systems and solar PV systems with MPPT control algorithms within the entire process, this study holds great significance. It is also urgently required to guide various stakeholders in determining the direction of future research, projects, and policies. Furthermore, research focused on ships operating in South Korea that integrate electric propulsion systems and Solar PV systems should be conducted to provide more detailed observations and assess their feasibility. Currently, there is a lack of in-depth environmental impact studies concerning such types of ships in the Korean maritime area. Therefore, this research is expected to play a pivotal role in explaining the potential environmental impacts associated with the adoption of electric propulsion ships in Korean maritime areas.

The outcomes of this research carry profound implications, as they hold the potential to advance the overarching objective of attaining net-zero emissions within the maritime sector. Moreover, this study is poised to furnish invaluable guidance to policymakers, industry stakeholders, and advocates for environmental sustainability. In so doing, it equips them with essential insights and pragmatic solutions necessary for charting a responsible course toward the future of environmentally conscious maritime transportation.



Comparing methods of environmental impact

	Scope	Pros	Cons
CII	TtW	• Updating Data	• Considering only the use/operation aspect • Only focusing on CO_2
Conventional LCA	WtW	• Holistic evaluation/analysis	• Using past data • Past performance • Replacing data that cannot be obtained with assumptions or guesses
Live LCA	WtW	• Updating Data • Holistic evaluation/analysis • Using actual data • Possible to obtain data that does not exist through modelling and simulation	-

Fig. 2. Necessity of LCA and the scope of each assessment.

2. Methodology

In this study, the Live Life Cycle Assessment (Live-LCA) methodology, proposed by Park *et al.*[2022], has been employed to gain a more precise understanding of the environmental impacts associated with the implementation of electric propulsion, Solar PV system, and MPPT for PV modules in ships as depicted in Fig. 3.

Conventional LCA method is inherently limited by its high reliance on existing data, and it often resorts to assumptions or estimations when necessary data is absent. Live-LCA method overcomes these limitations by introducing an additional step called "data generation". Through this approach, it can be derived more precise and context-specific environmental impact results compared to those obtained through traditional LCA, addressing critical shortcomings.

Furthermore, to assess the effectiveness of the electric propulsion system and Solar PV system, modelling and simulation using MATLAB/Simulink, as depicted in Fig. 4, are conducted. Specifically, an MPPT algorithm is designed and applied to the Solar PV system to appropriately track the maximum power point and simulate energy production. This ensures optimal energy generation from the solar panels, yielding results consistent with real-world scenarios. These activities enable the acquisition of suitable and reliable data without the need to construct or retrofit actual vessels with those systems. This process aligns with the "Data generation" aspect of Step 2 - LCI in Live-LCA.

The collaboration between these two methods allows for a more precise evaluation of the effectiveness of applying the electric propulsion system and MPPT applied Solar PV systems to vessels operating in South Korea.

2.1 Key feature of Live-LCA

Excessive reliance on existing data has, thus far, posed a significant obstacle to achieving accurate and situational environ-

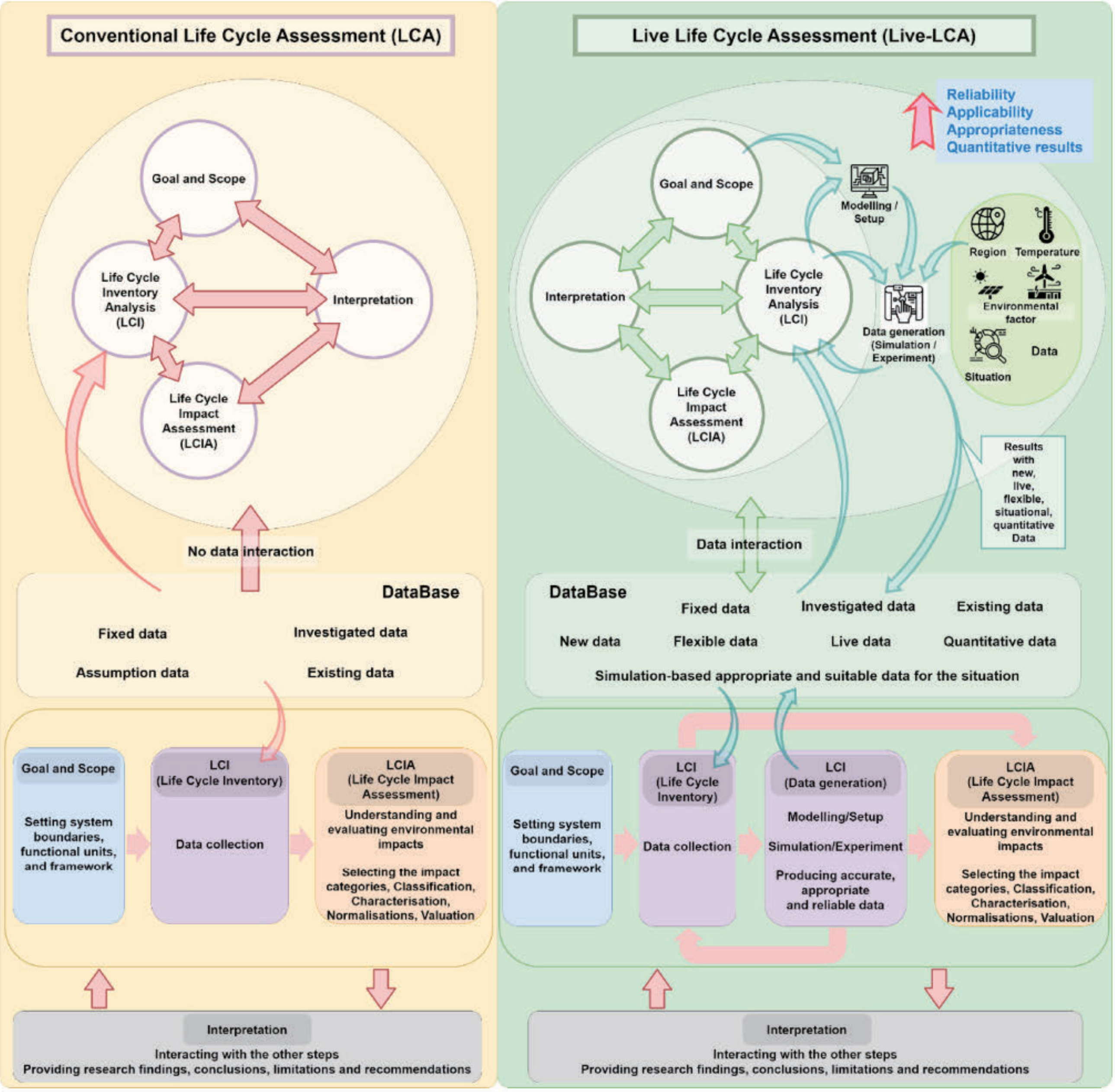


Fig. 3. Live-LCA methodology compared to conventional LCA.

mental impact assessments in LCA. This is particularly challenging in processes like maritime shipping, which sail under continuously varying conditions, environments, and operations. Shipping produces constantly changing data, therefore collecting/securing the data is essential to determine the environmental impact. However, acquiring all such data has practical limitations. Consequently, the absence of input data has led to results derived through assumptions and estimations, undermining both the credibility and applicability of these outcomes in diverse scenarios.

To address this challenge, the introduction of the Live-LCA methodology is proposed and implemented as a suitable remedy. Live-LCA relies on data generation through modelling/simulation or experimentation to obtain data that is presently unavailable. Therefore, it greatly enhances the ability to derive context-specific environmental impacts compared to conventional LCA. This enhancement significantly improves the reliability and applicability of research findings.

Notably, the maritime industry has been adopting various fuels and systems to protect the environment. On the other hand, for those kinds of new technology, not only data for vessels equipped with electric propulsion systems and Solar PV

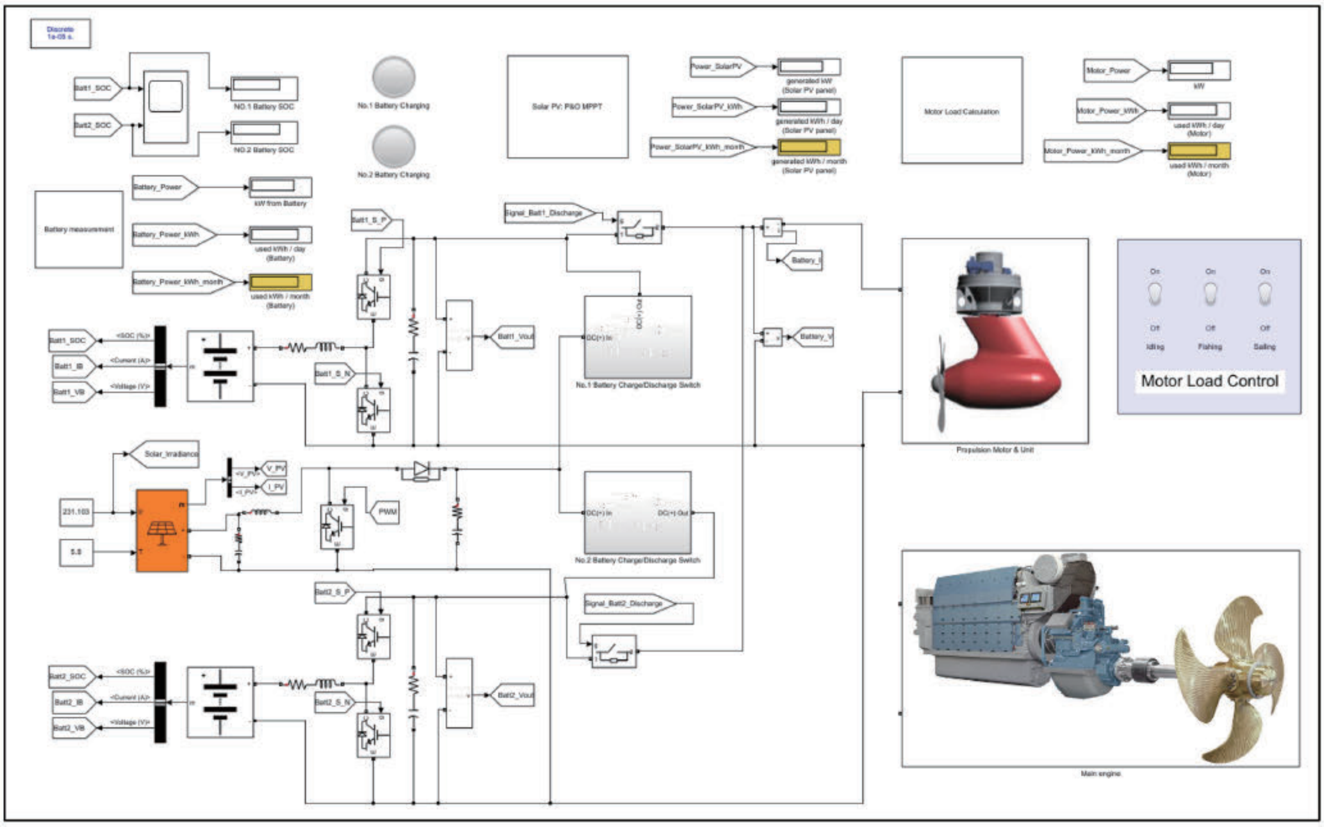


Fig. 4. Modelling of Electric propulsion system and Solar PV system using MATLAB/Simulink.

systems is, for the most part, not enough, but actual operational records are also quite limited. Additionally, the environmental impact of converting existing vessels to electric propulsion and operating them on the same routes is heavily reliant on databases filled with numerous assumptions and estimations, which compromise the accuracy and reliability of results. Live-LCA effectively addresses these issues, enabling extensive data collection and appropriate assessments through simulations of various scenarios.

In essence, this methodology offers substantial significance by extending the applicability of LCA techniques, traditionally suitable for static conditions, to dynamic situations.

2.2 Steps of Live-LCA

The steps of Live-LCA have been designed to follow the framework specified in ISO 14040, and they also adhere to the requirements outlined in ISO 14044. Consequently, the following steps are executed in accordance: Step 1. Goal and Scope; Step 2. Life Cycle Inventory Analysis (LCI); Step 3. Life Cycle Impact Assessment (LCIA); Step 4. Interpretation.

In the first step, “Goal and Scope”, the research objectives are defined, and why this environmental impact assessment is being conducted and how the results will be utilised are clearly explained. Additionally, the scope of the study is established and the system boundaries are delineated between what is included and excluded from the study. During this process, it is needed to make decisions regarding the functional unit, quantifying the evaluation criteria into measurable units. In this stage, there is no distinction between traditional LCA and Live-LCA; both follow the same process.

In the second stage, known as “LCI,” significant differences between conventional LCA and Live-LCA emerge. This stage involves identifying and quantifying inputs such as materials and energy resources and outputs like environmental emissions and waste generated in the product/system/process. Ultimately, the reliability of the database secured in this stage plays a crucial role in determining the success of the entire research. Conventional LCA heavily relies on existing data to construct its database. However, Live-LCA takes a different approach, striving to eliminate assumptions and estimations wherever possible. This is achieved through modelling, simulation, or experimentation to continuously produce context-specific data for database flexibility. Therefore, Live-LCA can contribute to deriving successful and appropriate research results by building a more accurate and reliable database.

The LCIA step uses the database established during the LCI stage to assess potential environmental impacts by converting them into specific impact indicators. LCIA includes essential sub-stages, such as Classification, which assigns the environmental load to selected impact categories, and Characterisation, which is for estimating results for category indicators. Additionally, optional sub-stages like Normalisation for provid-

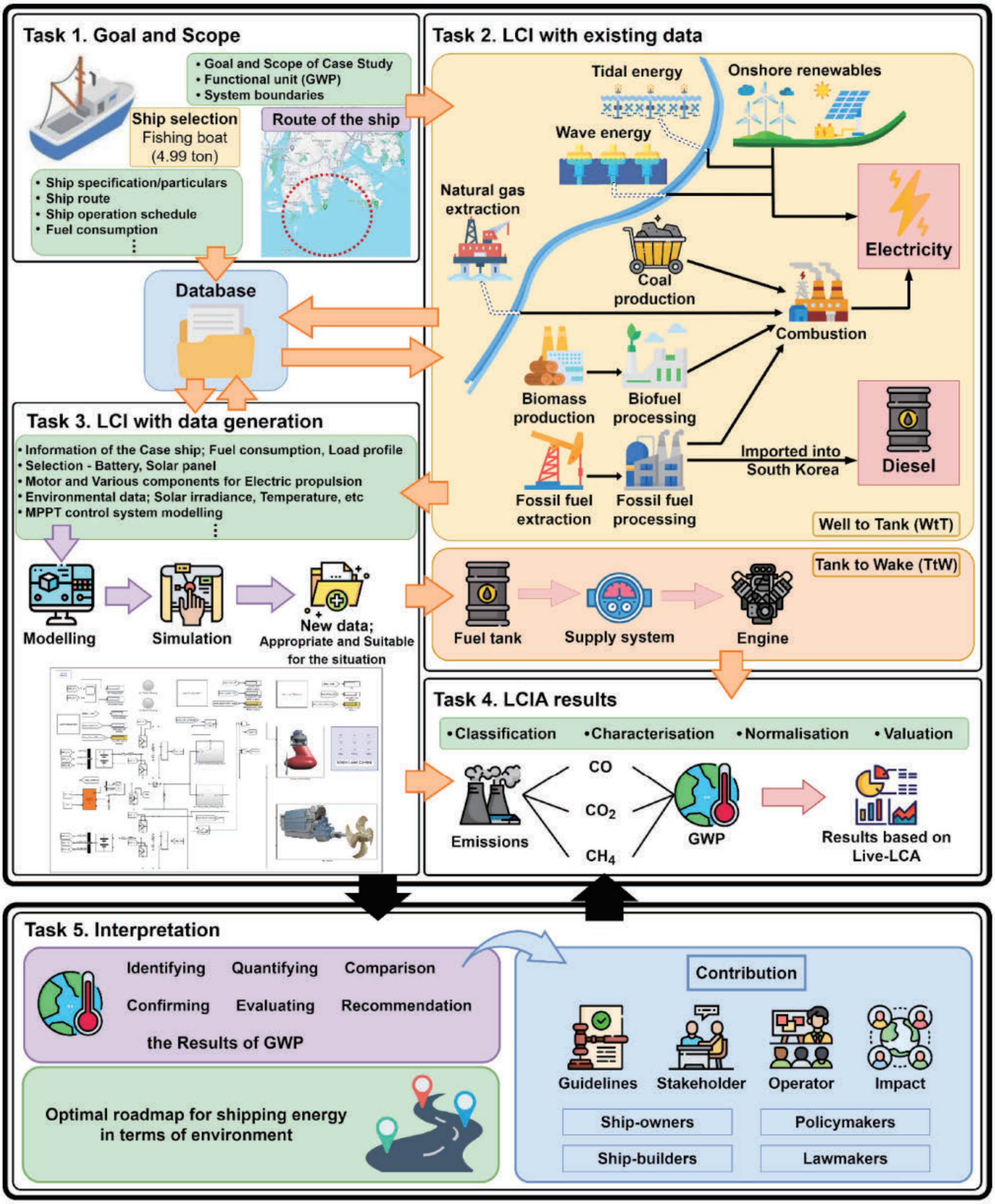


Fig. 5. Outline of the case study.

ing references for consistency, and Weighting, which aggregates scores based on derived weights, can be applied.

Finally, in the step of Interpretation, information collected, classified and characterised in the LCI and LCIA stages is identified, verified, and evaluated. Essentially, this stage determines the accuracy of the outcomes generated in previous stages and, ultimately, whether the results align with the objectives set in the "Goal and Scope" step. Continuous interaction with other stages and various methods to validate the data used are of utmost importance. Ultimately, this stage is responsible for drawing research conclusions and providing insights into limitations and practical recommendations.

3. Case study

The purpose of conducting this case study is to assess, review, and evaluate the contribution of the Electric Propulsion System and MPPT-applied Solar PV System when implemented in vessels operating in South Korea, towards making the maritime industry more environmentally friendly and achieving net-zero goals. In this case study, we applied the Live-LCA methodology introduced earlier to comprehensively and accurately determine the environmental impact of these new systems. Fig. 5 provides an overview of the entire case study conducted in this research.

3.1 Task 1. Building a database and setting research scope (Step 1: Goal and Scope)

The goal of this research is to assess the environmental viability of ships equipped with the electric propulsion system and Solar PV system controlled by MPPT algorithm in South Korea in comparison to conventional fossil fuel-based ships. To achieve this goal, the research scope involves selecting a conventional fossil fuel-based case ship and collecting its operational profile data. Based on this data, energy usage and resulting environmental impact comparison will be conducted for the same case ship navigating with electric propulsion and with the application of the electric propulsion system and Solar PV system. According to this plan, three cases will be considered in this research as follows and Fig. 6;

· Case 1: Fossil fuel-based mechanical propulsion system
· Case 2: Electric propulsion system powered by batteries
· Case 3: Electric propulsion system powered by batteries with Solar PV system controlled by MPPT

Case 2 and Case 3 are not from the actual existing ship but scenarios assumed for the purpose of verifying their feasibility in terms of the environment. Accordingly, reliable data for these scenarios needs to be obtained through appropriate modelling based on actual data. In Case 2, unlike Case 1, electric propulsion motors are installed instead of the main engine. The energy source for propulsion is electricity rather than MGO, and this electricity is obtained from South Korea's national power grid during the ship berth, stored in the ship's batteries, and used during navigation. The overall concept of Case 3 is similar to Case 2. However, in Case 3, the propulsion energy is not solely supplied by the stored electricity from the national power grid but is also supplemented by the electricity generated by the Solar PV system, which is stored in the batteries and used in conjunction with the grid electricity. In this case, the Solar PV system is continuously controlled to maximise

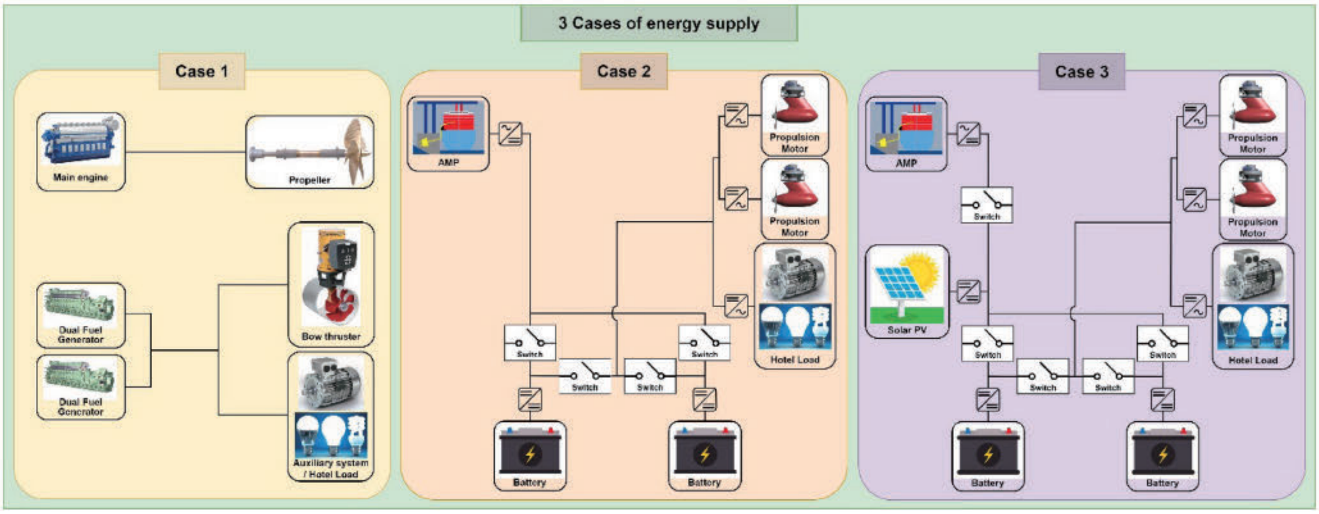


Fig. 6. Three cases of energy supply scenarios for the case ship.

power production through MPPT.

Based on the research and findings from these three cases, the ultimate goal is to ascertain whether electric propulsion ships and, furthermore, vehicles equipped with electric propulsion systems in South Korea indeed bring environmental advantages. Additionally, this research aims to provide insights into the current state of electricity production in South Korea by comparing environmental impact results when ships operating in South Korea use electricity produced domestically versus electricity produced in other countries with the same energy consumption. The final objective of this study is to offer direction for regulations and policies regarding the energy sector.

In this case study, the focus will be on GHG emissions for the three cases of the case ship, and the environmental impact will be assessed using the Global Warming Potential (GWP, kg CO_2 equivalent) as the default functional unit. Furthermore, the scope of the study does not include ship equipment and devices. From a holistic perspective of the Well-to-Wake (WtW) scope, encompassing viewpoints from production to consumption and disposal, the research concentrates on the fuels responsible for over 90% of emissions generated by ships, as they are central to understanding the environmental impact.

3.1.1 Case ship selection

In this case study, a fishing boat with a Gross Tonnage of 4.99 tons was selected as the case ship. This vessel has a Length Over All (L.O.A) of 15.06 meters, a Moulded Breadth (B) of 2.74 meters, and is equipped with a main engine with a capacity of 238 kW for propulsion. It operates in the waters off the coast of Busan, following a daily sailing route that departs from and returns to the harbour.

3.1.2 Case study framework

The framework of this case study, enabled by the application of the Live-LCA methodology, has expanded the boundaries of goal and scope setting compared to conventional LCA research, which typically involves a simple process from steps 1 to 4.

Live-LCA allows for data generation processes, making it adaptable and capable of defining extensive goals and scopes. The study involves refining the energy consumption of the electric propulsion system, which does not currently exist, and the energy production from the Solar PV system with MPPT through iterative simulations, using ship data. It employs the vessel's operational data, data on MGO supplied in South Korea, and information on electricity production in the Korean national power grid as independent variables. Parameters such as solar panel characteristics and local weather conditions are used as mediators to assess the correlation between environmental performance and experimental variables.

3.2 Task 2. LCI with existing data (Step 2: LCI)

3.2.1 Case 1: Fossil fuel-based mechanical propulsion system

According to the operational profile of the case ship, the vessel consumes approximately 98 kg of MGO per day. This MGO is imported as crude oil from overseas and undergoes refining processes in South Korea. Consequently, the environmental impact of the MGO used in South Korea is detailed in Table 1 (Hwang *et al.* [2019]).

3.2.2 Case 2: Electric propulsion system powered by batteries

In Case 2, the primary source of energy for the ship is electricity produced in South Korea. This electricity is transmitted to the ship through the national power grid, stored in the ship's batteries, and used during navigation. Based on the findings from the original operating mode of the case ship, which is Case 1, it was determined that the total energy required for the ship to consume approximately 98 kg of MGO per day is 475 kWh.

Using this scenario as a basis, the case ship was modelled with an electric propulsion system. Additionally, to understand the environmental impact generated during the ship's operation in this scenario, the production process and environmental impact factors of the electricity generated for South Korea's national power grid were examined, as illustrated in Fig. 7 and Table 2 (International Energy Agency (IEA)[2020]).

3.2.3 Case 3: Electric propulsion system powered by batteries with Solar PV system controlled by MPPT

Table 1. Functional unit of GWP for MGO refined and supplied in South Korea

MGO Functional unit	Well-to-Tank (WtT)	Tank-to-Wake (TtW)	Well-to-Wake (WtW)
GWP (kg CO_2 eq./kg MGO)	1.504	3.256	4.761

Table 2. Functional unit of GWP for electricity of national grid in South Korea

South Korea Electricity Functional unit	Well-to-Tank (WtT)	Tank-to-Wake (TtW)	Well-to-Wake (WtW)
GWP (kg CO_2 eq./kWh)	0.541	-	0.541

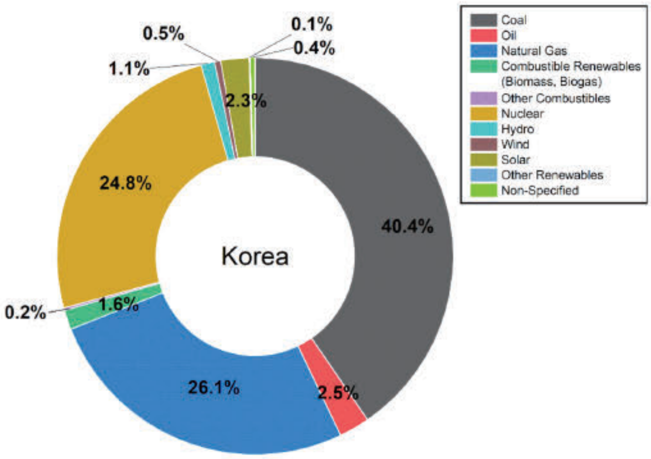


Fig. 7. Energy sources used to produce electrical energy for the national power grid of South Korea.

In this case, similar to Case 2, the electric propulsion system serves as the primary propulsion system, utilising electricity stored in batteries as an energy source during navigation. Not only this, the Solar PV system continuously provides power to the batteries. The batteries store and supply a combination of electricity from the national power grid and electricity generated by the solar panels.

To assess the environmental impact of this case, the parameters required for generating electrical energy from the Solar PV system were obtained from RETScreen, based on the operational route information of the case ship. Furthermore, the environmental impact per unit of electricity produced by the solar panels was determined (Jeong *et al.* [2020]). All information is summarised in Table 3.

Table 3. Environmental parameters and Functional unit of Solar PV system

Environmental parameters on the coast of Busan for Solar PV system			
Month	Daytime hours (h)	Irradiance (W/m^2)	Temperature (℃)
Jan	10.10	236.562	3.1
Feb	10.92	276.660	4.8
Mar	11.95	300.523	8.6
Apr	13.05	344.722	13.7
May	13.98	344.120	17.5
Jun	14.46	305.716	20.7
Jul	14.25	279.293	24.1
Aug	13.46	313.429	25.9
Sep	12.41	279.718	22.2
Oct	11.32	292.460	17.5
Nov	10.36	251.955	11.7
Dec	9.87	231.103	5.8
Functional unit of Electricity by Solar PV system			
Functional unit	Well-to-Tank (WtT)	Tank-to-Wake (TtW)	Well-to-Wake (WtW)
GWP (kg CO_2 eq./kWh)	0.0671	-	0.0671

Table 4. Solar panel selection and total capacity of Solar PV system

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	20
Array	5 series × 4 parallel
Voltage at MPP	286.5 V
Power capacity	6.94 kW

3.3 Task 3. LCI with data generation by modelling and simulation (Step 2: LCI)

3.3.1 Modelling

Defined scope, case ship selection and secured operational profile in Task 1, and the various data collected during Task 2 served as the basis for conducting electric propulsion ship modelling using MATLAB/Simulink, as illustrated in Fig. 4.

Propulsion motors with the total capacity to produce the same output as the existing case ship's main engine were utilised. Battery capacity was set to be sufficient for a day's operation, and to ensure the appropriate storage and continuous supply of power generated by the Solar PV system, batteries were configured as two sets. Consequently, when one set of batteries supplies power, the power generated by the solar PV system is stored in the other set of batteries. This system design was implemented to ensure the safe and consistent supply of power to the load, even when there is significant variability in the power generated by the Solar PV system.

Assuming that solar panels cover approximately 80% of the ship's surface area, a total of 20 solar panels could be installed, considering the ship's size. A type of Solar panel was selected based on models available in MATLAB/Simulink that closely match those of efficiency used in recent industry applications. Consequently, the total installed power capacity was 6.94 kW at 25? and 1000 W/m^2. The specifications and modelling status of the solar panels are detailed in Table 4.

As per Table 4, when modelling the Solar PV system in MATLAB/Simulink, the graph depicting the maximum current

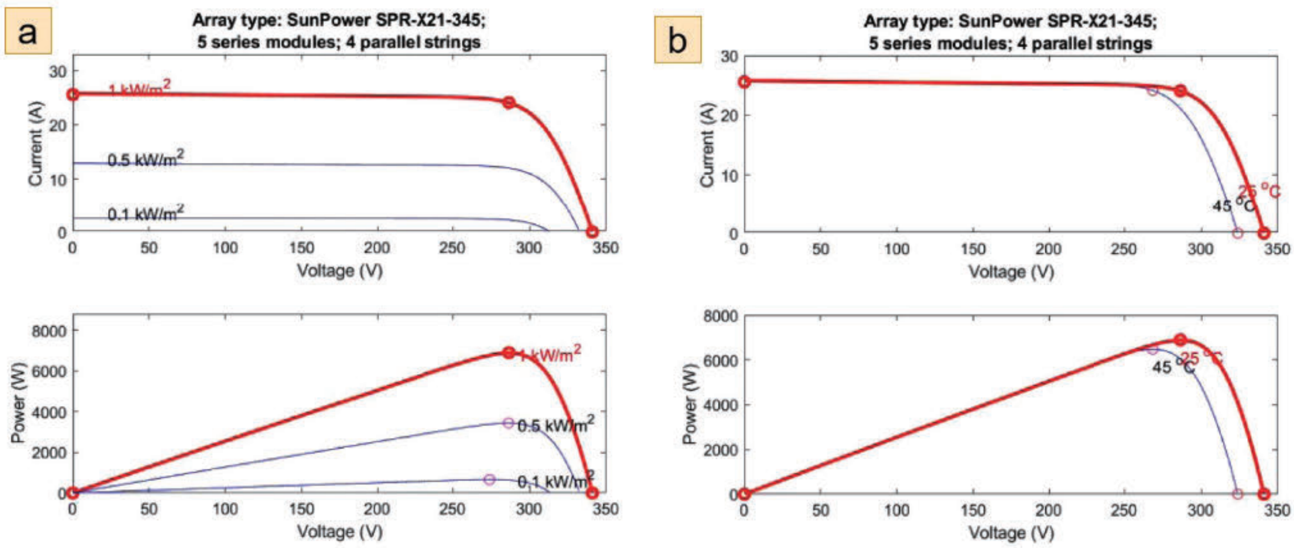


Fig. 8. Graphs of Maximum Current (A) and Power (W) depending on the voltage produced by installed solar panels; (a) Graphs at 25℃, (b) Graphs at 1000 W/m^2 irradiance.

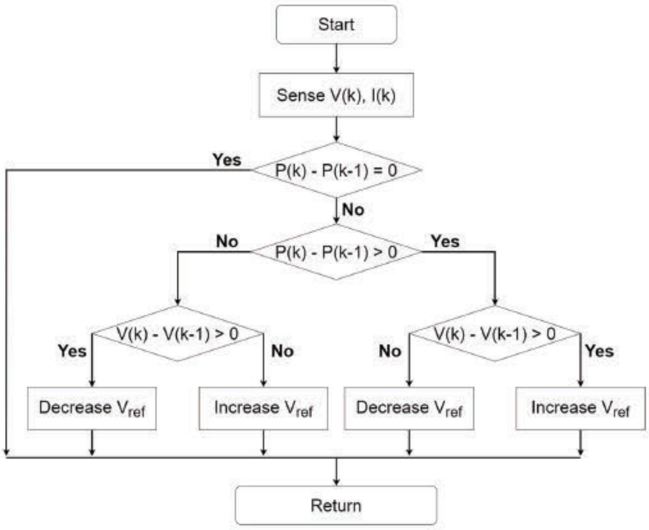


Fig. 9. Conceptual diagram of Maximum Power Point Tracking.

and power based on the voltage generated by the installed solar panels is as Fig. 8 below.

Furthermore, to consistently maintain the optimal output of the Solar PV system, which varies due to constantly changing environmental parameters, the MPPT algorithm was incorporated into the modelling. Fig. 9 illustrates the basic conceptual diagram of the MPPT algorithm applied in the modelling.

The modelling and simulation results were compared with the case ship's operational profile and energy consumption, confirming the proper functioning of the electric propulsion system.

3.3.2 Data from simulation

In the Goal and Scope phase, the specific areas required for modelling for each case of the selected case ship were established, as illustrated in Fig. 10. Consequently, during the simulation phase, simulations were conducted for each case scenario by appropriately including or excluding equipment and devices to align with the respective scenarios.

Simulation through the modelling based on Tabl 3, and the MPPT algorithm, yielded the necessary data to confirm the effectiveness of Case 3. This data was compiled in Table 5, taking into consideration that when the case ship operates with an electric propulsion system, it requires approximately 475 kWh of energy per day. The energy supply from the Solar PV system and the battery was divided accordingly. The environmental parameter values presented in Table 3 represent the monthly averages for the waters off Busan. Therefore, in the same way, Table 5 summarises the monthly average power production capacity of the installed Solar PV system when the case ship operates in that region.

3.4 Task 4. LCIA results (Step 3: LCIA)

Based on the data collected in Task 1-3, the environmental assessment of the fuels and energy used in the three cases considered for the case ship was conducted. Among various environmental impact assessment methods, this research employed the CML 2001 method as the reference. The assessment was carried out with a focus on GWP, following the boundaries established in the Goal and Scope step. Consequently, the daily GHG emissions values for each case of the case ship are presented in Table 6.

When estimating the ship's lifespan as 30 years, configuring

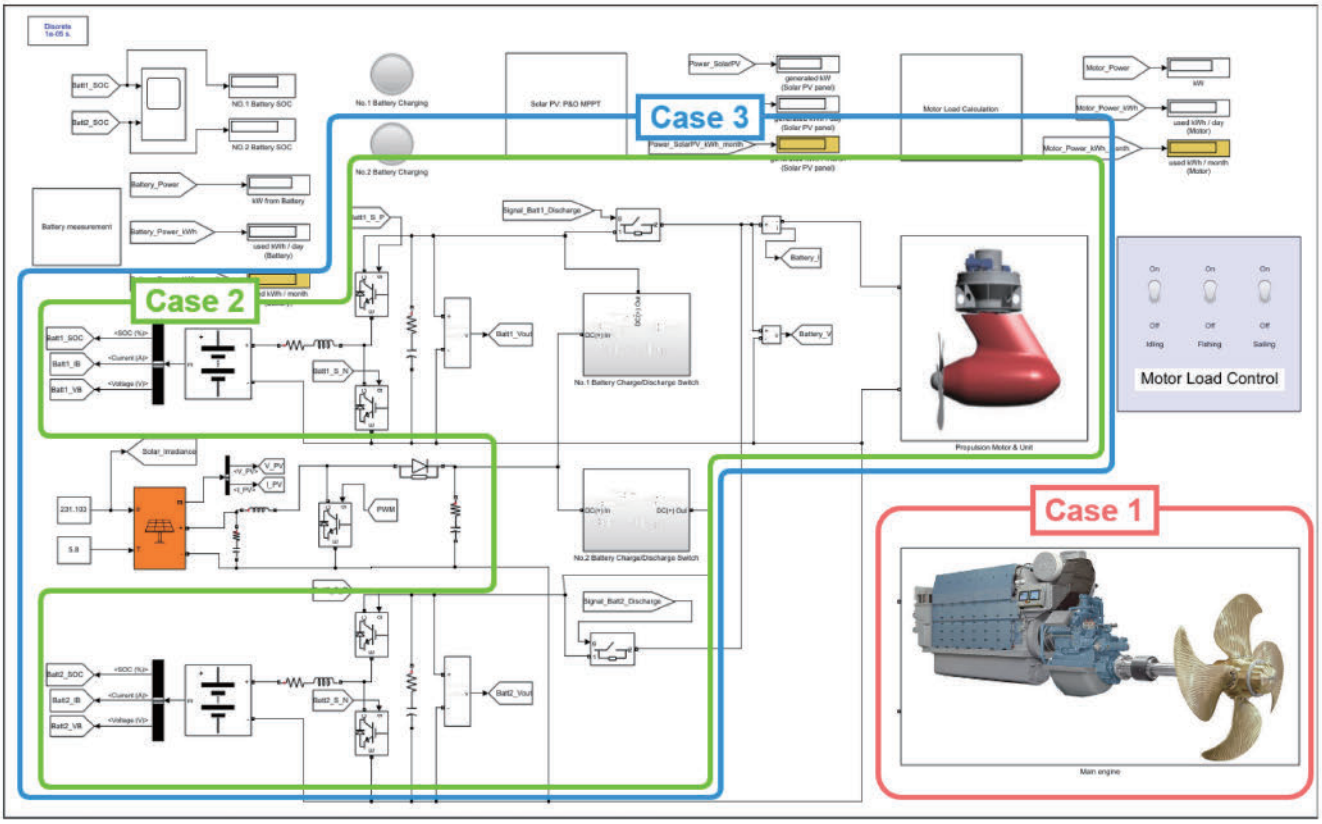


Fig. 10. Established areas for each case in modelling for the case ship.

Table 5. Simulation results for Solar PV system on the case ship

	Required energy	475 kWh / day
Month	Required energy from Battery (kWh/day)	Supplied energy from Solar PV system (kWh/day)
January	464.9	10.1
February	460.8	14.2
March	457.1	17.9
April	450.5	24.5
May	448.8	26.2
June	452.6	22.4
July	455.9	19.1
August	453.2	21.8
September	458.3	16.7
October	458.7	16.3
November	463.4	11.6
December	465.5	9.5

Table 6. Daily GHG emissions values for each case of the case ship

Case 1		Case 2	
GWP (kg CO_2 eq./day)	466.5	GWP (kg CO_2 eq./day)	257.2
Case 3			
Month	GWP (kg CO_2 eq./day) from Electricity supplied by		
	Battery	Solar PV system	Total
January	251.7	0.68	252.4
February	249.5	0.95	250.4
March	247.5	1.20	248.7
April	243.9	1.64	245.5
May	243.0	1.76	244.7
June	245.0	1.50	246.5
July	246.8	1.28	248.1
August	245.4	1.46	246.8
September	248.1	1.12	249.2
October	248.3	1.09	249.4
November	250.9	0.78	251.7
December	252.0	0.64	252.6

the case ship's systems according to each case scenario and operating them based on the current navigation route and operational profile, the total GWP that could occur over the lifespan of the case ship is depicted in Fig. 11.

The research findings indicate that when transitioning a conventional fishing boat using MGO to an electric propulsion system, as in Case 2, only 55% of GHG emissions are generated. Furthermore, when incorporating an MPPT-applied Solar PV system as in Case 3, an additional GHG emission reduction of approximately 2% can be achieved for the case ship.

3.5 Task 5. Interpretation (Step 4: Interpretation)

Comparative analysis between the user perspective and LCA

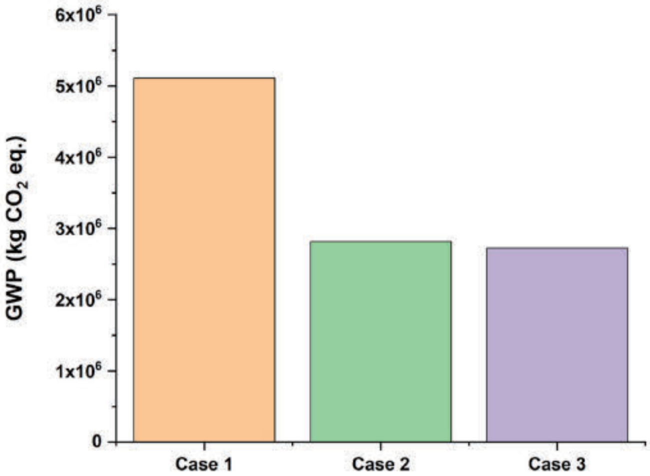


Fig. 11. Total GWP of the case ship during lifespan depending on each case.

As illustrated in Fig. 2, many studies and regulations have traditionally assessed the environmental impact of new systems or energy sources from a user-centric perspective. Additionally, most existing regulations have also applied and evaluated compliance with regulations solely from a user-centric standpoint. According to this perspective, the electric propulsion system and the Solar PV system with MPPT, as reviewed in this paper, are considered emission-free clean energy sources, capable of achieving a 100% reduction in GHG emissions as compared to Case 1. In other words, when evaluating the environmental impact exclusively from a user perspective, the study estimates that 5.11×10^6 CO_2 eq., generated over the lifecycle of the case ship, are saved from a single ship.

However, as clearly demonstrated in Fig. 1, from a holistic perspective that considers the entire lifecycle, electric energy exhibits significantly different environmental impacts depending on how it is produced. In other words, when electricity which is generated solely by coal is used on ships, it can actually have worse environmental impacts from a WtW perspective than ships powered by diesel. Furthermore, even when renewable energy sources such as solar and wind, considered as completely clean energy sources, are used to produce electricity, they still result in GHG emissions due to the equipment and operations required for electricity generation.

LCA is a comprehensive approach that allows for the consideration of these factors. In this study, it has been appropriately applied to determine that, contrary to common perception, electric propulsion ships equipped without/with Solar PV systems generate only 55% and 53% GWP respectively, compared to scenarios using MGO fuel.

3.5.2 Comparative analysis between the conventional LCA and Live-LCA

As explained in Section 2.1, conventional LCA heavily relies on existing data to assess environmental impacts. In cases where such data is lacking, it either excludes them from the scope of the study or resorts to assumptions and estimations to derive results. The scenarios proposed in this study involve transitioning a fishing boat, which operates using MGO, to the electric propulsion system or an electric propulsion ship equipped with MPPT-applied solar PV system, all while maintaining the same route and operational profile. However, real-world ship and operational data for such scenarios do not exist. Consequently, employing the conventional LCA method would require making assumptions and estimations for all these data points.

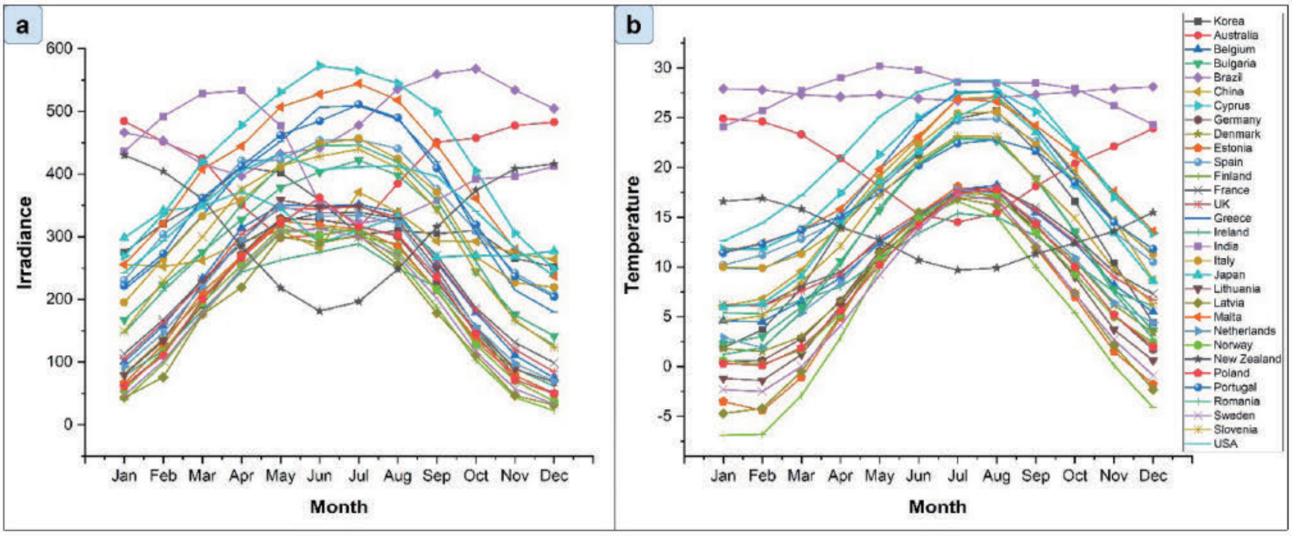


Fig. 12. Environmental parameters by month by country; (a) Irradiance, (b) Temperature.

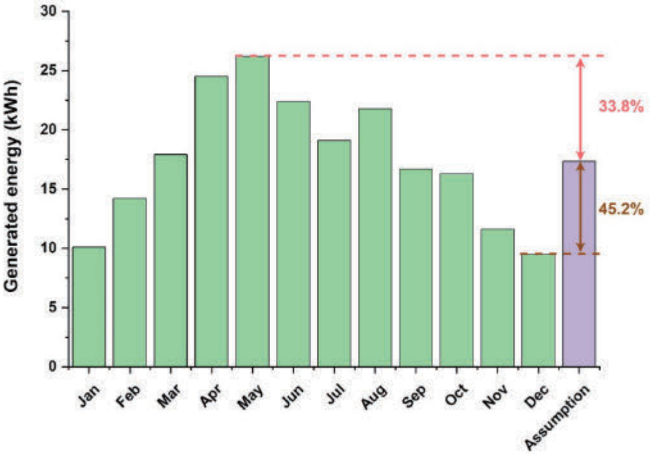


Fig. 13. Comparison of actual and assumed electric energy generated by the Solar PV system installed on the case ship.

Conducting research in this manner often leads to results that significantly deviate from reality. This is because, as depicted in Fig. 12, actual environmental impacts can not only significantly depend on various parameters but also vary considerably with time, location, and circumstances.

In particular, the Solar PV system is highly sensitive to these environmental parameters, leading to significant variations in the generated electrical power. Fig. 13 illustrates the amount of electric energy produced by the Solar PV system in Case 3 scenario, taking into account the environmental parameter data from the actual route of the case ship operating in the Busan Sea.

As a result, it was observed that, as depicted in Fig. 12, significantly different amounts of energy are generated over time due to varying parameter values. However, the conventional LCA methodology does not engage in such processes. In the absence of data, it relies solely on assumptions to estimate energy production. Based on this methodology, the calculated electrical energy production, assuming a total power capacity of 6.94 kW for the installed Solar PV system on the case ship and a daily efficiency of 25% for 10 hours, can be seen in Fig. 13. This assumption value can be different significantly; for instance, during May, when the Solar PV system generates the most power, the assumption is about 33.8% lower, while during December, when it produces the least power, it is about 45.2% higher. Such calculated value remains consistent and is applied uniformly in conventional LCA, regardless of the operating region, date, or weather conditions, thereby undermining the accuracy and reliability of research results.

3.5.3 Effectiveness of Electric propulsion ship with Solar PV system

Through this research, it has been conclusively confirmed that electric propulsion ships operating in South Korea, equipped with/without MPPT-applied Solar PV systems, can offer significant environmental benefits. A fishing boat weighing 4.99 tons, operating in the waters off Busan, emits a total of 5.11×10^6 CO_2 eq. GHG over its lifespan. In contrast, when the same vessel is designed to operate with an electric propulsion system based on the same navigation route and profile, it emits only 2.82×10^6 CO_2 eq. GHG over 30 years. Furthermore, by integrating an MPPT-applied Solar PV system with the electric propulsion system, it is possible to achieve reduced emissions in GHG of up to 2.72×10^6 CO_2 eq.

The effectiveness of the electric propulsion system and MPPT-applied Solar PV system has been demonstrated in the case of one fishing boat. If the scope of this research is extended to encompass South Korea's fishing boat fleet, a total of 65,531 vessels registered as of 2022 as indicated by Table 7, it will further emphasise the system's effectiveness (Ministry of Oceans and Fisheries[2022]).

Among these, fishing boats weighing 5 tons or less number 52,460, accounting for a substantial 80% of the total, and the vessel selected as the case ship falls within this mainstream category. Therefore, assuming that vessels weighing 5 tons or less are operated based on the same navigation route and profile as the case ship, the effectiveness of the electric propulsion system can be more clearly confirmed. In the existing scenario, Case 1, it generates approximately 8.93×10^9 CO_2 eq. annually. In contrast, in Case 2, it amounts to 4.92×10^9 CO_2 eq., and in Case 3, it is only 4.76×10^9 CO_2 eq. In other words, by converting all fishing boats weighing 5 tons or less in South Korea to the electric propulsion system and operating them over a 30-year lifespan, a total reduction of approximately 1.20×10^{11} CO_2 eq. in GHG emissions can be achieved. Additionally, by incorporating an MPPT-applied Solar PV system into the electric propulsion system, approximately an extra 4.78×10^9 CO_2 eq. can be reduced.

In summary, the reduction in GHG emissions obtained by

Table 7. Number of fishing boats by tonnage in 2022 in South Korea

Tons	0-1	1-2	2-5	5-10	10-50	50-200	> 200	Total
Number	13,104	20,736	18,620	9,194	2,709	864	304	65,531

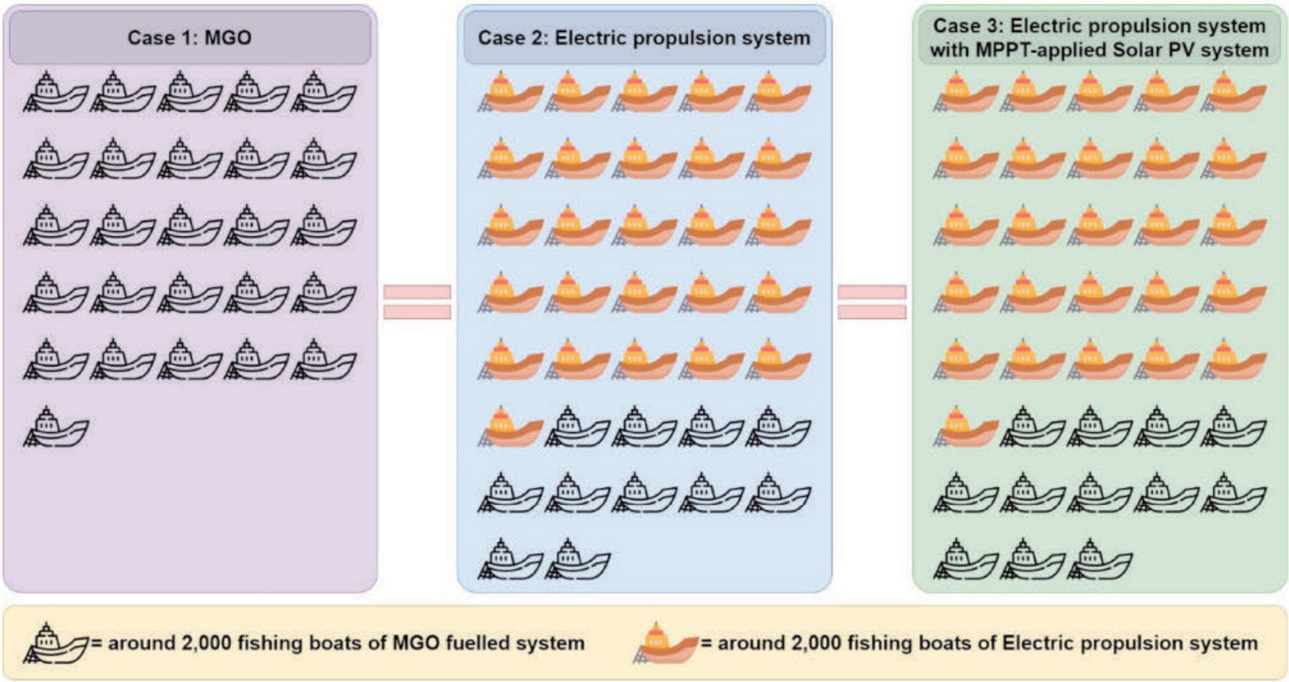


Fig. 14. Effectiveness of Electric propulsion system and MPPT-applied Solar PV system.

converting all fishing boats weighing 5 tons or less to electric propulsion systems, as shown in Fig. 14, is equivalent to the emissions generated by approximately 23,540 vessels of the same size operating with MGO over their lifetimes. Furthermore, the GHG emissions from approximately 24,480 vessels operating over their lifetimes with MGO can be offset through the use of an electric propulsion system with MPPT-applied Solar PV system. Moreover, under the same Case system, in the Case 2, approximately 42,710 electric propulsion fishing boats could be additionally operated over their lifetimes, and based on Case 3, about 45,900 fishing boats based on electric propulsion with solar PV system could be further put into service.

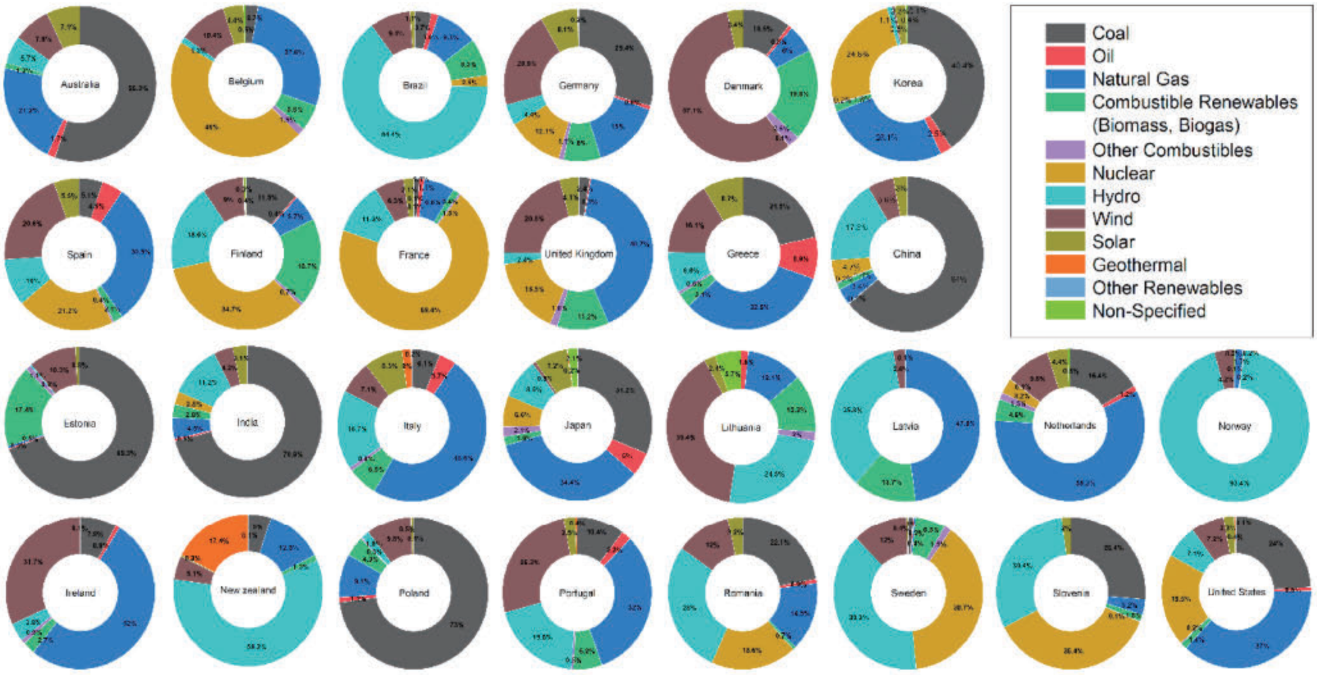


Fig. 15. Energy sources to produce electric energy for the national grid.

3.5.4 Insight into energy system of South Korea

The effectiveness of the electric propulsion system and Solar PV system compared to fossil fuels has been conclusively demonstrated. However, the benefits from these systems can exhibit distinctly different patterns depending on the method of electricity generation and various environmental factors such as weather. Consequently, it is essential to investigate how the effectiveness of the electric propulsion system, which has been identified as having significant environmental benefits, might vary and to provide directions for policies and regulations to further enhance its effectiveness.

Fig. 15 shows the proportion of energy sources used for electricity generation supplied to power grids in several countries, including South Korea (International Energy Agency (IEA)[2020]). This reveals that, from a WtW perspective, using the same quantity of electrical energy can yield totally different environmental impact results in line with Fig. 1.

In addition, the country-specific GWP values per unit of electricity for 30 countries provided by GaBi are shown in Table 8 (Sphera Solutions[2023]). Based on this data, the environmental impact results over the lifecycle of the selected case ship, operating under the same schedule and profile but powered by electricity produced in different countries, are depicted in Fig. 16.

Fig. 16 clearly illustrates that the environmental impact results vary significantly depending on which country the electricity used to operate the case ship was produced. When using electricity produced in South Korea, GHG emissions are nearly halved compared to when using MGO as fuel. However, when electricity produced in Estonia and India is used, it leads to even greater GHG emissions compared to using MGO. This is attributed to the higher reliance on coal in these countries for electricity generation, as depicted in Fig. 1 and Fig. 15. In addition, for Australia and Poland, the environmental impact difference between using electric energy and MGO is negligible. In other words, in Australia, Estonia, India, and Poland, the electric propulsion system is either ineffective compared to fossil

Table 8. The functional unit of GWP value per kWh for 30 countries

Country	GWP ($kg\ CO_2$ eq./kWh)	Country	GWP ($kg\ CO_2$ eq./kWh)
Australia	0.981	India	1.06
Belgium	0.173	Italy	0.477
Bulgaria	0.728	Japan	0.632
Brazil	0.296	Lithuania	0.225
China	0.812	Latvia	0.162
Cyprus	0.823	Malta	0.638
Germany	0.544	Netherlands	0.522
Denmark	0.279	Norway	0.027
Estonia	1.17	New Zealand	0.149
Spain	0.417	Poland	0.971
Finland	0.193	Portugal	0.5
France	0.0928	Romania	0.449
UK	0.309	Sweden	0.0375
Greece	0.756	Slovenia	0.354
Ireland	0.518	USA	0.512

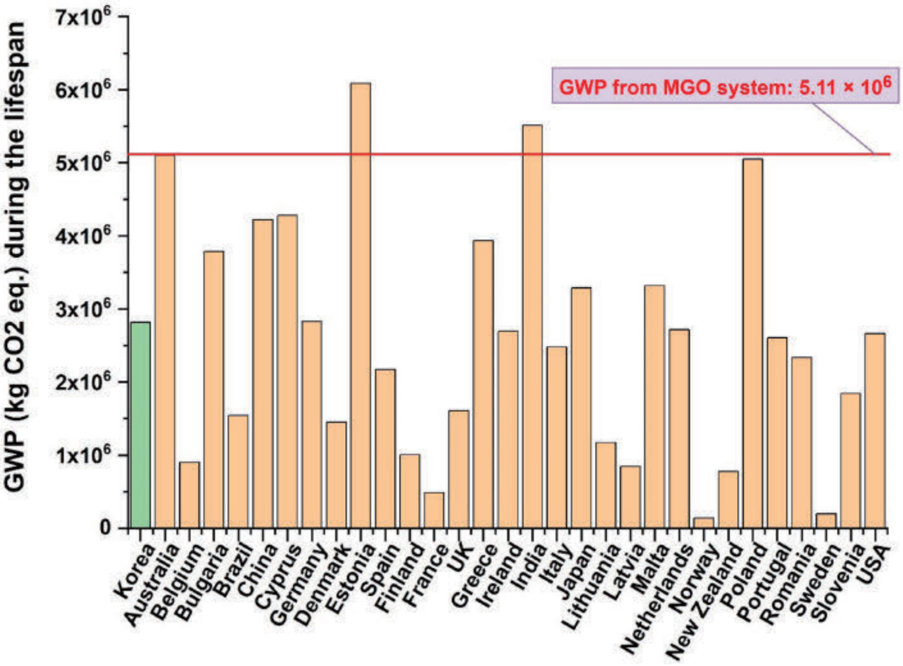


Fig. 16. Case ship GWP during the lifespan based on national grid electricity of several countries.

fuel systems, or it even leads to environmentally severe consequences.

In contrast, countries like Norway, France, and Sweden, where a significant proportion of electricity is generated through renewable and nuclear sources, show remarkably high effectiveness of the electric propulsion system. In the case of South Korea, which currently relies on coal for about 40% of its electricity production, it ranks 20th in environmental impact results among the 31 countries investigated. This highlights that rather than maintaining the current state, a focus should be placed on producing more electricity through renewable energy sources, similar to other advanced nations, to contribute significantly to mitigating global warming.

These research findings extend beyond electric propulsion ships alone. Electric vehicles are replacing fossil fuel vehicles not only in South Korea but in many countries worldwide. Therefore, a systematic reorganising and greening of national power systems can have a far-reaching impact beyond the environmental results presented in this study. In essence, enhancing the efficiency of electric propulsion systems and greening electricity production for improved environmental outcomes represent a critical and inescapable current challenge, as well as a sustainable step forward for future generations.

4. Discussion

4.1 Research achievements

First and foremost, the most significant novelty of this research lies in its methodology. In conventional LCA, the scope of the study has been strongly affected by the availability of data. Even when aiming to delve deeper into environmental impacts, data limitations constrained the study's boundaries, limiting its scalability and becoming a clear factor in reducing the reliability, accuracy, and precision of research outcomes. However, the Live-LCA introduced in this study not only collects existing data in a conventional way but also relies on accumulating data obtainable through data generation and extracts/utilises the desired and necessary data through appropriate means. This audaciously overcomes the limitations of conventional LCA and allows for an infinitely expandable boundary. Consequently, it eliminates constraints on the scope of the study and significantly enhances the reliability, accuracy, and applicability of research results.

Furthermore, in this study, modelling enabled the integration of the electrical propulsion system into the case ship along with the Solar PV system instead of the conventional MGO-fuelled mechanical propulsion system. This provides environmental insights into scenarios where approximately 52,460 fishing boats of similar types and sizes are converted into electric propulsion ships or ships with integrated Solar PV systems. These research findings can serve as valuable foundational information for stakeholders involved in future shipbuilding and design decisions. They not only offer guidance to policymakers and rulemakers but also provide substantiated evidence for future directions.

Lastly, this research enables a detailed evaluation and consideration of the electric propulsion system, which is spotlighted not only in maritime transport but also in inland vehicle, by incorporating an evaluation of the South Korean national power grid. Given that the environmental efficiency of electric propulsion systems is significantly influenced by the environmental footprint of the electricity they consume, this study generates meaningful results that can further encourage sustainable practices and greening policies.

4.2 The direction of future study

This study involved the modelling of the electric propulsion system and MPPT-applied Solar PV system based on the operational profile, engine load, route, etc. of a real fishing boat. In essence, it verified the suitability of the modelling by implementing systems that do not exist and ensuring that simulation results aligned with the actual ship's operational data. However, certain aspects, such as battery weight, installation area, and battery degradation, were not included within the scope of this research. Consequently, future research is to encompass an extended scope that considers these factors. It aims to plan and execute evaluations regarding additional emissions resulting from appropriate modelling that accounts for variations in power demand based on the ship's weight and degradation of sources.

Furthermore, recent research has considered and studied fuel cell systems linked to various fuels, in electric propulsion systems. Reflecting this industrial trend, it is crucial to conduct robust research on electric propulsion systems that include fuel cell systems and investigate how these systems can be appropriately integrated and controlled in conjunction with solar PV systems and battery systems.

Lastly, environmental impact is not the sole focus moving forward. Sustainability is increasingly emphasised, necessitating exploration of systems that can be used continuously over extended periods. To achieve this, comprehensive research addressing not only the environment but also the societal (safety) and economic (cost) aspects, integral components of sustainability, is imperative. In other words, there is a need for research that evaluates the safety and cost of electric propulsion systems, in line with this study. In particular, with regard to installing a solar PV system on small ships, advanced research is needed to determine the effectiveness of the emission reduction effect compared to the cost. Moreover, it is essential to assess whether these systems can indeed be sustainably utilised, providing outcomes that can contribute to stakeholders.

5. Conclusions

The key finding of this study is that demonstrates the environmental benefits of implementing the electric propulsion system in small vessels operating in South Korea through the introduction of Live-LCA and modelling. Furthermore, the superiority of the methodology has been validated by confirming that applying a Solar PV system to the case ship and assessing its effectiveness through the conventional LCA method can result in errors of up to approximately 45%.

From a WtW perspective, when the case ship operates based on an electric propulsion system in South Korea, it emits only about 55% of GHGs compared to when it operates using a mechanical propulsion system fuelled by MGO. Furthermore, with the addition of an MPPT-applied Solar PV system, the electric propulsion system can reduce GHG emissions to approximately 53% of the original level. Thus, if all fishing boats under 5 tons operating in the coastal waters of South Korea were to switch to electric propulsion systems based on the same load and operational profile as the case ship, they could achieve a reduction of approximately 1.20×10^{11} CO_2 eq. in GHG emissions during their lifespan. In addition, the installation of MPPT-applied Solar PV system could further reduce GWP, approximately 1.25×10^{11} CO_2 eq.

Lastly, this study has proven that the expectation that systems using electric energy will be environmentally friendly, often held as a vague belief, is not necessarily true from a holistic perspective. The research results demonstrate that in some countries, electric propulsion systems can, in fact, contribute to more severe global warming than fossil fuels, and there are cases where system changes do not yield any benefits. Therefore, this study suggests the need for a review of approaches that can fundamentally demonstrate environmental protection effects, rather than blindly directing efforts towards electric propulsion systems. The research results emphasise the significance of greening the production of electric energy.

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